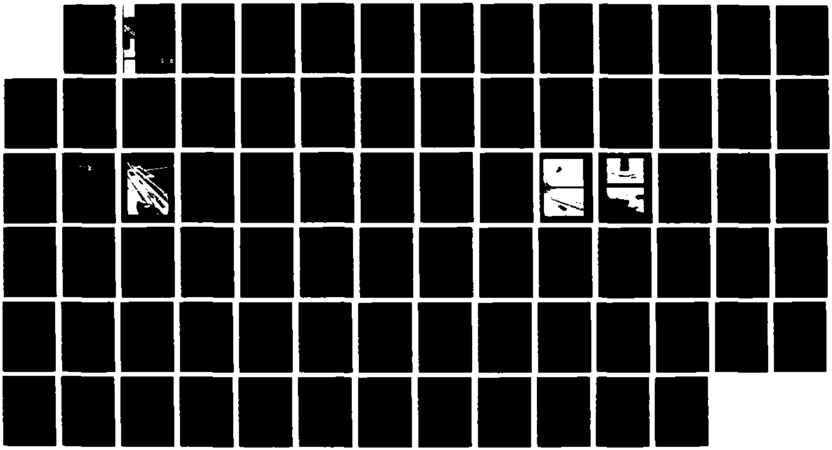
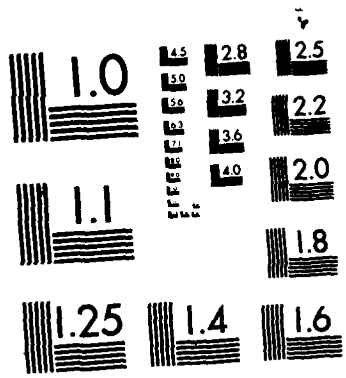
AD-A181 207 SAFE NAVIGATION SPEEDS AND CLEARANCE AT LOWER SILL 1/1
TEMPORARY LOCK 52 OHIO RIVER(U) ARMY ENGINEER WATERWAYS
EXPERIMENT STATION VICKSBURG MS HYDRA.. S T MAYNARD
UNCLASSIFIED APR 87 WES/TR/HL/87-3 F/G 13/2 NL





MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

DTIC FILE COPY

(12)

TECHNICAL REPORT HL-87-3

US Army Corps of Engineers

SAFE NAVIGATION SPEEDS AND CLEARANCE AT LOWER SILL, TEMPORARY LOCK 52, OHIO RIVER

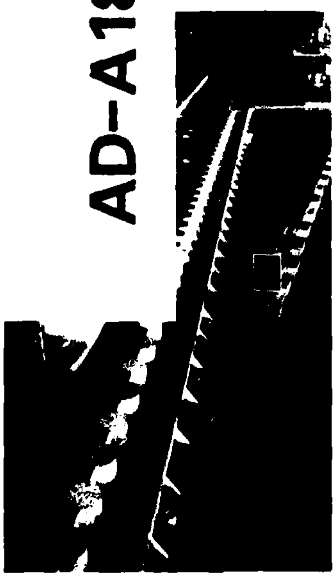
by

Stephen T. Maynord

Hydraulics Laboratory

DEPARTMENT OF THE ARMY
Waterways Experiment Station, Corps of Engineers
PO Box 631, Vicksburg, Mississippi 39180-0631

AD-A181 207



April 1987

Final Report

Approved For Public Release; Distribution Unlimited

DTIC
ELECTE
JUN 5 1987
S D
A

HYDRAULICS LABORATORY

Prepared for US Army Engineer District, Louisville
Louisville, Kentucky 40201-0059

Unclassified
SECURITY CLASSIFICATION OF THIS PAGE

A181207

REPORT DOCUMENTATION PAGE

Form Approved
OMB No 0704-0188
Exp Date Jun 30, 1986

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) Technical Report HL-87-3	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION USAEWES Hydraulics Laboratory — 6b. OFFICE SYMBOL (If applicable) WESHS-S	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State, and ZIP Code) PO Box 631 Vicksburg, MS 39180-0631	7b. ADDRESS (City, State, and ZIP Code)
8a. NAME OF FUNDING/SPONSORING ORGANIZATION USAED, Louisville — 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code) PO Box 59 Louisville, KY 40201-0059	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO / PROJECT NO / TASK NO / WORK UNIT ACCESSION NO

11. TITLE (Include Security Classification)
Safe Navigation Speeds and Clearance at Lower Sill, Temporary Lock 52, Ohio River

12. PERSONAL AUTHOR(S)
Maynord, Stephen T.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final report	FROM ________ TO ________	April 1987	84

16. SUPPLEMENTARY NOTATION
Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Hydraulic models (LC); Inland navigation (LC); Lock and Dam 12, Ohio River (WES); Locks (Hydraulic engineering) (LC); Towing (LC)

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This investigation has identified four possible mechanisms for producing tow squat, the vertical drop of the tow due to motion, measured from the still water level, in the temporary lock at Locks and Dam 52. Based on tests with tows either self-propelled or pulled with a towing apparatus, this investigation shows that squat for entering tows is determined by different parameters from those for exiting tows. The maximum squat for almost every self-propelled test (entering or exiting) was located at the stern of the towboat. For loaded tows entering the lock, the primary mechanism producing squat was propeller squat. Because tests involving entering tows using the towing apparatus produced very little squat, it was concluded that tow speed is not a significant cause of squat for entering tows. For loaded tows exiting the lock, propeller squat is still an important mechanism for producing squat. This importance was illustrated by the acceleration tests, during which all the tows approached the sill at the same speed. Squat

(Continued)

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE (Include Area Code) / 22c. OFFICE SYMBOL

19. ABSTRACT (Continued).

increased for increased propeller speed. The towing tests show tow speed to be another significant factor in defining squat for exiting loaded tows. It was not determined whether this squat was displacement or piston squat. Unloaded exiting tows also have the potential for enough squat to strike the lower sill when operating at high propeller and tow speed. It is likely that displacement, propeller, and moment squat all contribute to the total squat for unloaded exiting tows. The downstream gates for the emptying flume should remain open during tow entry/exit. Entry/exit speeds were higher with the valves open. For equal tow speeds, squat is considerably less with the valves open.

PREFACE

The model study of the temporary lock at Locks and Dam 52 was authorized by the US Army Engineer Division, Ohio River (ORD), on 9 January 1985. Pertinent information to conduct the study and the funding were provided by the US Army Engineer District, Louisville (ORL).

The study was conducted during the period April 1985 to December 1985 by personnel of the Hydraulics Laboratory of the US Army Engineer Waterways Experiment Station (WES) under the direction of Messrs. F. A. Herrmann, Jr., Chief of the Hydraulics Laboratory, and J. L. Grace, Jr., Chief of the Hydraulic Structures Division. The tests were conducted by the following Spillways and Channels Branch (S&CB) personnel: Messrs. S. T. Maynord, Project Engineer, W. B. Fenwick, R. Bryant, E. L. Jefferson, G. Gleason, and J. R. Rucker, and Mmes. J. McAlpin, J. A. Flowers, and L. Turner under the direct supervision of Mr. N. R. Oswalt, Chief, S&CB. The model was constructed by Messrs. Ed Case and Dennis Rushing of the Engineering and Construction Services Division. This report was written by Mr. Maynord and edited by Mrs. Marsha Gay, Information Technology Laboratory.

During the course of the investigation, Messrs. Glen Drummond, Dave Pattison, and Laszlo Varga of ORD, and Larry Curry, Gene Allsmiller, Truman Emerson, and Dave Beatty of ORL visited WES to observe tests and/or to discuss test results.

COL Allen F. Grum, USA, was the previous Director of WES. COL Dwayne G. Lee, CE, is the present Commander and Director. Dr. Robert W. Whalin is Technical Director.

A-1

CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
degrees (angle)	0.01745329	radians
feet	0.3048	metres
horsepower	745.6999	watts
inches	2.54	centimetres
square feet	0.09290304	square metres

SAFE NAVIGATION SPEEDS AND CLEARANCE AT LOWER SILL, TEMPORARY LOCK 52, OHIO RIVER

PART I: INTRODUCTION

The Prototype

1. Locks and Dam 52 is a low-lift navigation dam with two locks located on the lower Ohio River near Paducah, Kentucky (Figure 1). Construction of the original Lock and Dam 52, which had a single 110- by 600-ft* lock, was completed in 1928. The existing dam is of the movable type with a 1,248-ft navigation pass, 540 ft of chanoine weir, 160 ft of bebout weir, three 91-ft beartraps with piers, and 725 ft of fixed weir for a total length of 2,998 ft. The dam has a navigable pass that can be lowered during periods of high flow to allow navigation to proceed over it unhindered. This high flow occurs an average of 60 percent of the year.

2. During the 1960's it became clear that the single 600-ft lock could not meet the immediate navigation needs, nor could a permanent improvement plan be brought on-line in time to avoid serious delays to commercial navigation. Accordingly, in 1969, a 110- by 1,200-ft temporary lock was completed at Locks and Dam 52. The lift for both the 600- and 1,200-ft temporary locks is 12 ft at normal pool. Details of the 1,200-ft temporary lock are shown in Plates 1 and 2, and an upbound tow is shown entering the temporary lock in Figure 2.

3. Towboats on the lower Ohio River passing through Locks and Dam 52 vary considerably with power ranging up to 8,500 hp and are propelled by open wheels or Kort nozzles. The majority of tows using the lock are close to 1,200 ft in length. Draft on barges varies from 2 ft (empty) to in excess of 10 ft.

Purpose of the Model Study

4. At low flow periods on the lower Ohio River, the lower pool

---

* A table of factors for converting non-SI units of measurement to SI (metric) units is found on page 3.

elevation of 290* provides only 11 ft of depth over the lower miter gate sill (el 279) of the temporary lock. At such depth, heavily loaded tows or tows traveling too fast have a great potential for striking the lower miter gate sill. On two occasions the sill has been struck and structurally damaged, halting operation of the 1,200-ft lock and causing severe delays in navigation. As a result of these accidents, the following draft restrictions are presently used to ensure safe navigation at Locks and Dam 52:

a. Effective immediately, when the lower gate at Locks and Dam 52 is 10 ft (depth over sill = 12 ft) or less, no towboat or barge with a draft in excess of 9 ft 3 in. will be permitted to pass through the 1,200-ft chamber. Vessels permitted to enter the 1,200-ft chamber must exercise extreme caution in the vicinity of the lower gate sill. "Slow speed" and "no driving over the lower sill" will be mandatory.

b. Tows with drafts in excess of 9 ft 3 in. will be locked through the 600-ft lock. Double locking in the 600-ft lock, which is normally not permitted when the 1,200-ft lock is operating, will be allowed while stages of 10 ft or less exist.

The purposes of this study were to determine the mechanisms that produce tow squat and to define combinations of speed, draft, and clearance that provide safe navigation through Locks and Dam 52.

Scope

5. The study began with a search of existing literature. Next a prototype investigation was conducted to observe tow operation at Locks and Dam 52. A physical model investigation using tows either self-propelled or pulled with a towing apparatus was then used to determine the mechanisms causing tow squat and to define conditions for safe navigation through the locks.

Potential Mechanisms for Producing Tow Squat

6. Tow squat is the vertical drop of the tow due to motion, measured from the still water level. Several possible mechanism for producing tow squat are discussed in the following paragraphs and will be addressed in the testing program.

---

* All elevations (el) and stages cited herein are in feet referred to the National Geodetic Vertical Datum (NGVD).

Displacement squat

7. Displacement squat is the traditional concept of tow squat in confined waterways which is presented by several investigators including Jansen and Schijf (1953).* Displacement squat occurs when the water adjacent to the tow is set into motion by the displacement of the tow. To maintain the same total energy, the water surface must drop by an amount equivalent to the kinetic energy of the moving water. This drop in water level results in squat of the tow. Displacement squat is related mainly to tow speed, ratio of tow cross-sectional area to waterway cross-sectional area, and depth of water. Since the propeller speed is unimportant for this type of squat, the results from the towing tests will be used to determine the importance of this mechanism for producing squat.

Piston squat

8. This mechanism is restricted to locks, because the channel is blocked at one end, and is significantly different for entering (upbound) versus exiting (downbound) tows. Entering tows tend to "pile up" water in front of the tow, which tends to give the tow a greater depth in which to float, particularly at the bow of the tow. Therefore piston squat is not possible for entering tows. For exiting tows, the opposite is true. As the tow leaves the lock, the volume behind the tow can be increasing at a greater rate than the return flow under and around the tow. If this happens, the water depth available behind the tow can decrease, causing squat, particularly of the towboat. This phenomenon is shown in Figure 3. Since this mechanism is not related to propeller movement, the results of the towing tests will be used to address the importance of this mechanism.

Propeller squat

9. Propeller squat is caused by the ability of the towboat to pump water from beneath itself faster than it can be replaced. This effect is significant only in shallow water and is enhanced by the presence of the barges upstream, which can block the supply of water to the propellers, particularly in a confined waterway such as a lock.

Moment squat

10. Moment squat (Figure 4) is caused by the offset between the force

---

* P. Ph. Jansen and J. B. Schijf. 1953. 18th Congress, Permanent International Association of Navigation Congresses; Section 1, Inland Navigation, Communication 1, Rome.

produced by the propellers and the force at the connection with the barges. This offset, which would be greatest with unloaded barges, produces a clockwise moment that tends to force the rear of the towboat down.

PART II: PERTINENT LITERATURE

11. Present guidance for gate sill depths is presented in ETL 1110-2-223* as follows:

a. Discussion. The guidance presented for selecting gate sill depth (SD) is not intended to reduce the established lock chamber depth (CD). Experience and research data indicate the SD's should be as great as practical to lessen tow entry and exit times and chamber surges during these maneuvers. A 2- or 3-ft-high gate sill (above chamber floor) or a local recess is often desirable to provide space for gate seating, maintenance work, inspection, and to keep sediment and debris out of the chamber.

b. Guidance.

(1) The lower gate sill is to be from zero to 3 ft high (above the chamber floor) when the CD is less than or equal to 2d + 3 ft [d = design vessel draft]. If the sill is set lower than 2 ft above the chamber floor, the floor should be recessed in the area of the gate to provide at least 2 ft clearance under the gate.

(2) When the CD is greater than 2d + 3 ft, the lower SD should be at least 2d.

(3) The upper SD should be at least equal to the lower SD.

(4) In establishing the upper SD, special operating conditions such as hinge pool operation and provisions for navigation of special equipment in case of loss of pool also should be considered. These considerations may result in a greater SD than would otherwise be required.

(5) Additional allowances for CD and SD over the above may be necessary for special conditions such as ice accumulations on bottoms of tows, debris, or sediment accumulations, etc.

The minimum sill depth at Locks and Dam 52 ($\approx$11 ft) is considerably less than the desired 2d $\approx$ 18 ft specified in ETL 1110-2-223.

12. Jansen and Schijf (1953)** presented a method of computing squat and limiting speed for ships or tows moving in a canal. Limiting speed is the tow speed at which critical flow (in the open channel flow sense) will occur adjacent to the tow. Self-propelled vessels cannot exceed this limiting speed regardless of the power applied. The Jansen and Schijf method requires

---

* Office, Chief of Engineers. 1977. "Navigation Lock Sill Depths and Hydraulic Loads on Gates," ETL 1110-2-223, Department of the Army, Washington, DC.

** Jansen and Schijf, op. cit.

constant speed, a uniform cross section, and absence of confining walls either upstream or downstream. All three of these requirements are violated by a tow moving in or out of a lock. Even though the Jansen and Schijf method cannot be used quantitatively at a lock, the concept of tow speed being limited by critical flow is valid. For comparison purposes only, the limiting speed and squat based on Jansen and Schijf's method are presented in Figures 5 and 6, respectively.

13. Kooman (1973)* discussed phenomena observed during tow entry and exit. Entry speed can be irregular due to formation of positive translation waves in front of the tow. Exit speed for loaded tows is often controlled by the limiting speed.

---

* C. Kooman. 1973. "Navigation Locks for Push Tows," Rijkswaterstaat Communications, Government Publishing Office, The Hague, The Netherlands.

PART III: PROTOTYPE INVESTIGATION

14. Early in this study a limited prototype investigation was conducted to observe tow movement and to measure tow speed and squat. Tow speed was obtained by measuring the time required for the tow to pass successive 50-ft intervals along the lock. Squat was measured by mounting a 30-ft level rod on the rear of the towboat and taking readings with a surveyor's level located on the lock wall. Prototype data are listed in Table 1, and results of the measurements are shown in Figures 7-16. The stationing used in these figures is the same as that posted on top of the prototype lock walls. The following general comments are based on observations made during the prototype investigation:

- a. There was a wide range in horsepower and towboat size. These variations resulted in different operational techniques at certain points during entering and exiting the lock.
- b. The rudder configuration varied with the different boats. The larger boats had Kort nozzles with a steering rudder behind the wheel and two backing (or flanking) rudders in front. The smaller boats had similar rudder arrangements but open wheels (no Kort nozzle). Wheel sizes and pitches also varied widely. One boat (*Omega*) had a controllable pitch wheel which varied from 1 to 5 deg.
- c. Another variation among tows was the arrangement of empty and loaded barges. There appeared to be no consistent trend to put loaded barges at front, rear, outside, or inside of the tow. The major consideration when making up a tow seemed to be the points of pickup and leaving of individual barges.
- d. Connections between the towboat and the tow were made up in many different ways. Occasionally the boat was set off to one side at the rear of a tow. Again, the major consideration when connecting the towboat to the tow had to do with the order of adding and dropping individual barges.
- e. All pilots used very low headway while entering and leaving the lock. Power was usually set in the range of 100-200 wheel rpm's. The pilots of larger boats cut the power off during the entire time the boat was over the sill. Some have learned to use the confining effect of the lock and their engines to actually increase their clearance over the sill by either pulling water under themselves or riding the returning lock wave. Sufficient headway is required to permit the boat to "coast" over the sill.
- f. Very little and very infrequent rudder was applied once the tow was lined up with the lock and was sheltered by the approach walls.

g. Pilots have been requested by the lock operators to traverse the lower sill under no power, i.e., coasting. This was done by several of the pilots.

h. Speed varied considerably from tow to tow along the lock chamber.

i. Squat was at a maximum (up to 0.8 ft) when the towboat was accelerating or decelerating. While tows were under way at a constant engine speed, the squat for all towboats varied from 0.1 to 0.65 ft. Squat was less than 0.1 ft when coasting. These measurements apply only to the stern of the towboat.

j. High forward thrust on the towboats observed produced significant squat. High backward thrust was not consistent from tow to tow. Some tows had the highest squat while using high backward thrust. Others rode up in the water (negative squat) for high backward thrust.

k. Tows entering the lock from downstream maneuvered slowly until their bow was in the confined section and the tow was aligned with the downstream wall. Then the tows came ahead with significant speed. Often, because of so many tows waiting, the upbound tows were tied off just below the lower miter gate.

l. In the past, the downstream culvert valve was often closed after the lower pool elevation was achieved in the lock. Lock operators are now leaving the valve open while the tows move in and out of the lock.

m. The operators suggested that the poor cell alignment at Locks and Dam 52 keeps the tow speed down.

n. Operators generally lock three tows up and then three tows down when tows are waiting.

o. The lock operators explained one of the problems with the present draft restriction is that for lower gage readings of 10.0 ft or greater, any draft tow can enter the lock. Once the gage falls below 10.0 ft, tows are restricted to 9 ft 3 in. and each barge has to be measured, which considerably slows the lockage time for each tow. A gage reading of 10.0 ft corresponds to a depth of 12.0 ft over sill.

p. The lock operators stated that some of the towboats draft in excess of 9 ft. Often tows come through which have towboats too small for the load being pushed.

q. The lower sill problem at Locks and Dam 52 is a case of having to regulate all tows because of the performance or loading characteristics of a very few tows. This lock operated for many years without a draft restriction and without damage to the lower sill. One pilot, either pushing a heavily loaded tow too fast or with excessive acceleration of the towboat while over the sill, damaged the lower sill and put the lock out of operation. The lock operators feel that a speed restriction combined with some type of draft restriction may be more effective than the present draft restriction only.

PART IV: THE MODEL

Description

15. A 1:20-scale model was used to reproduce the 1,200-ft lock and 1,200 ft of the downstream approach to the lock (Figure 17). Initially, the model was constructed without the side filling and emptying flume. After the initial test series, the side filling flume, downstream culvert, and manifold were placed in the model. The model was then operated with the emptying valves open at all times. Corrugated sheet metal was used to reproduce the roughness of the sheet pile cells forming the riverward lock wall. The lower miter gate sill (Figure 18) was formed of Styrofoam to prevent damage to the model towboat.

16. The model towboat (Figure 17) simulated a prototype towboat having twin 9-ft-diam open wheels, two main and two flanking rudders, a length of 209 ft, a 44-ft beam, and a draft which was varied from 9 to 10 ft. Towboat draft was always equal to the barge draft being tested except for tests with unloaded barges. The variable speed towboat engines were battery powered, and the towboat was operated by a person onboard. Barges modeled in this investigation were 35 ft wide by 195 ft long with drafts up to 10 ft. The barges were lashed together to form a tow three barges wide by four barges long. The bows of the lead barges were raked, and the sterns of the rear barges had boxed ends. Barge draft was varied using sand ballast. Towboat draft was varied using lead and masonry weight. To represent the prototype most accurately, the connection between the model towboat and barges was flexible.

17. Data collected during the study included tow speeds, propeller speed, squat, draft, and depth over the lower sill. Tow speed was obtained by measuring the time required for the tow to pass successive 200-ft intervals along the lock. Squat was measured at the bow of the lead barge, the midpoint of the barges, the stern of the rear barge (equal to the bow of the towboat), and the stern of the towboat. The four staff gages used for squat measurement are shown in Figure 17. The squat measurements were taken as the staff gage passed over the lower sill. All depths were measured relative to the top of the lower sill.

18. A simple towing device was used in a small portion of the tests to pull the tow in and out of the lock. The towing line was attached to the lead

barge and placed at an elevation that would not cause a significant upward or downward force on the front of the barge.

Scaling Relations

19. The equations of similitude based on Froude's Law

$$\text{Froude number (Model)} = \text{Froude number (Prototype)} = \frac{V}{\sqrt{gL}} \tag{1}$$

where

V = velocity, ft/sec

g = gravity, ft/sec^2

L = characteristic length, ft

were used to express mathematical relations between the dimensions and the hydraulic quantities of the model and prototype. The following relations were used:

Dimension	Ratio	Scale Relations
Length	$L_r = \frac{\text{Prototype Length}}{\text{Model Length}}$	1:20
Time	$T_r = L_r^{1/2}$	1:4.47
Velocity	$V_r = L_r^{1/2}$	1:4.47
Weight	$W_r = L_r^3$	1:8,000
RPM	$R_r = 1/L_r^{1/2}$	1:0.224

However, frictional resistance of ships is dependent on the Reynolds number

$$R = \frac{VL}{\nu} \tag{2}$$

where ν is the kinematic viscosity, ft^2/sec. The model and prototype Reynolds numbers are different when the same fluid is common to both model and prototype, and the Froude criteria are used as the basis for similitude.

Using different Reynolds numbers results in greater friction forces in the model, causing slower tow speeds in the model compared with those in a prototype having similar propeller thrust. Some ship studies increase propeller thrust by increasing revolutions to achieve the correct ship speed. This approach could not be used in this investigation because the pumping action of the propellers is one of the primary causes of tow squat. However, because of the large model used in this investigation, tow speed in the model should not be significantly less than in the prototype. Any differences in tow speed were further minimized by modeling a 1,000-ft-long prototype tow instead of the 1,200-ft-long tow normally encountered in the prototype. A comparison of tows two barges long with tows four barges long showed that tow length is not a significant factor for tow squat in a lock.

PART V: TESTS AND RESULTS

Tests with Emptying Flume and Downstream Culvert

Self-propelled tests, loaded barges

20. Table 2 summarizes the results of all tests. The following tests were conducted using the towboat to propel the barges:

	Depth Over Sill, ft			
Draft, ft	11.0	11.5	12.0	12.5
9.0	x	x		
9.5	x	x	x	
10.0		x	x	x

x = test conducted for this condition.

These tests were conducted for both entering upbound and exiting downbound tows using a wide range of propeller speeds. No tests were conducted with entering downbound or exiting upbound tows since the tow did not cross the lower sill for these conditions. All tests began with the tow stationary. Tests with entering tows were begun with the bow of the lead barge located 100 ft downstream of the beginning of the confining section of the lock. Tests with exiting tows were begun with the stern of the towboat against the upper miter gate. For each test the propeller speed remained constant throughout the entering and exiting maneuver. Results of the selected individual tests are shown in Plates 3-18. Stationing used in these plots is consistent with the stationing shown on Plate 1. Results showing maximum squat versus tow speed are summarized in Figures 19 and 20. Maximum squat versus propeller speed is summarized in Figures 21 and 22. The maximum squat for the self-propelled tests was almost always at the stern of the towboat. The speed of the entering tows was irregular due to the formation of translation waves. Tows having the same clearance (depth over sill minus draft) had about the same squat for the same propeller speed. All values shown are in prototype units unless noted otherwise. A summary plot showing the relationship of squat, clearance, and propeller speed is shown in Figure 23. Static clearances of 2.5 ft between sill and tow maintained at least 1 ft of clearance while the tow was under way for all propeller speeds. Static clearances of 1.5 and 2.0 ft resulted in less than 1 ft of clearance while the tow was under way.

Towing tests, loaded barges

21. A second series of tests was conducted using the towing mechanism to pull the tow in and out of the lock. All conditions were similar to those of the propulsion tests except that the propellers were not turning. These tests were conducted in an attempt to separate the displacement or piston squat from the squat caused by the propellers pumping the water out from beneath the tow. Tests were necessary with only one draft (10.0 ft) to study the different squat producing mechanisms. Results for the entering and exiting tows are summarized in Figures 24 and 25, respectively. Results from selected individual tests are shown in Plates 19-24. The entering tows show almost no squat for all speeds tested during towing. This indicates displacement squat is not significant for loaded entering tows since it is related to tow speed. The exiting tows show increasing squat with increasing speed for towing. The maximum squat for the towing tests was located at the stern of the rear barge for almost every test. Comparisons of results from the towing tests with results from the propulsion tests should be used with caution because the propulsion tests had significant variation of tow speed while the towing tests had a constant tow speed. Another series of towing tests was conducted using a variable speed similar to the self-propelled tests. Results are shown in Figure 26. The maximum squat for each test versus speed approaching sill and speed over sill are summarized in Figure 27.

Self-propelled tests, unloaded barges

22. A limited series of tests was conducted using unloaded barges with a draft of 2.0 ft, a towboat draft of 9.5 ft, and a depth over sill of 12 ft. The unloaded upbound entering tows observed during the prototype investigation used very little power entering the lock. Unloaded downbound exiting tows were strongly affected by crosswinds and occasionally had to use considerable power in the vicinity of the lower sill. For this reason, only exiting tows with the unloaded barges were tested. These tests were conducted with the tow approaching the sill at a speed of approximately 1 to 1.5 ft/sec and then accelerating when the stern of the towboat was 150 ft from the lower sill. Maximum squat, shown in Figure 28, occurred when the rear of the towboat was over the sill. Rudders were maintained straight ahead, which resulted in considerably higher tow speeds compared with those of tows fighting a strong crosswind. These tows would have to use hard left rudder.

Tests Without Emptying Flume and Downstream Culvert

Self-propelled tests, loaded barges

23. An initial test series was conducted using the model without the lock emptying flume and culvert. Selected individual test results are shown in Plates 25-28. Observation of these tests and initial test results showing excessive squat suggested that the emptying flume and culvert should be added to the model. Results are summarized and compared with the results using the flume and culvert in Figures 29 and 30. Speeds are higher for both entering and exiting the lock with the culvert installed. Squat, for the same tow speed, is decreased with the culvert. The irregular entry speed caused by translation waves was more pronounced without the emptying flume and culvert.

Acceleration tests, loaded barges

24. Tests were conducted to demonstrate the effect of an increase in propeller speed when the towboat is in the vicinity of the lower sill. The results of these tests, conducted for an exiting tow, are summarized in Figure 31.

Moment Squat Tests

25. A series of tests was conducted to address the possibility of moment squat (see paragraph 10) using the tow in a large depth of unconfined waterway. Squat was measured with the loaded tow initially stationary for a range of propeller speeds. Results are shown in Figure 32. These tests showed relatively small squat for the loaded tow for all propeller speeds. These tests were repeated with unloaded barges (draft $\approx$2.0 ft) and a towboat draft of 9.5 ft. Results (also shown in Figure 32) show greater squat for the unloaded tows and increasing squat for increasing propeller speed.

PART VI: CONCLUSIONS AND RECOMMENDATIONS

26. Based on tests using both self-propelled tows and a towing apparatus, this investigation has identified four possible mechanisms for producing tow squat in navigation locks and has shown that squat for entering tows is caused by different parameters from these causing squat for exiting tows. For the tow used in this investigation, combinations of speed, draft, and clearance were determined that provide safe navigation through Locks and Dam 52. Static clearances of 2.5 ft between sill and tow maintained at least 1 ft of clearance while the tow was under way for all propeller speeds. For static clearances of less than 2.5 ft, propeller speed had to be limited to maintain 1 ft of clearance while the tow was under way.

27. The maximum squat for almost every self-propelled test (entering or exiting) was located at the stern of the towboat.

28. Because the towing tests of entering tows produced very little squat, tow speed is not important for entering tows. Since displacement, piston, and moment squat have been shown to be either small or inapplicable to entering loaded tows, propeller squat is the primary mechanism producing squat.

29. For exiting loaded tows, propeller squat is still an important mechanism for producing squat. This was illustrated by the acceleration tests, during which all the tows approached the sill at the same speed but showed increased squat for increased propeller speed. The towing tests show tow speed to be another significant factor in defining squat for exiting loaded tows. It was not determined whether this mechanism was displacement or piston squat.

30. Entry speed can be very irregular due to the formation of translation waves. These waves are caused by the tow moving from the unrestricted waters into the confining section of the lock. The irregular entry speed caused by the translation waves was more pronounced in the tests without the emptying flume and culvert.

31. Unloaded exiting tows also have the potential for enough squat to strike the lower sill when operating at high propeller and tow speed and low clearance between tow and sill.

32. The downstream valves for the emptying flume should remain open during tow entry/exit. Entry/exit speeds were higher with the valves open.

For equal tow speeds, squat is considerably less with the valves open.

33. Speed of tow entry and exit at the shallow depths in Lock 52 will be very low because of the limiting speed concepts discussed in Part II. Towboat captains passing through the lock will have to be patient.

34. Large towboats are susceptible to striking the lower sill because they have the greatest draft and the greatest potential for producing propeller squat. Small towboats may be susceptible to striking the lower sill because they may have to use increased power while in the vicinity of the lower sill.

35. The one-dimensional squat models (displacement squat) used in confined waterways* are nct applicable to squat in navigation locks.

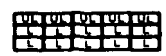
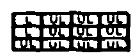
36. The primary weakness of this study was that one towboat and pilot were used in the model whereas an almost infinite variety exists in the prototype. Consequently, the squat/propeller speed/draft relations for the model towboat cannot be strictly applied to all prototypes. But identification of the primary variable controlling tow squat in navigation locks, namely propeller speed, can enable the solution of the problem.

---

* Jansen and Schijf, op. cit.

Table 1

Data from Prototype Investigation

Towboat	Travel Direction*	Towboat: Hp	Towboat: Wheel	Towboat: Length × Width ft	Towboat: Draft, ft	Barges**: Configuration	Barges**: Barge Draft, ft	Lower Gage (Depth Over Sill), ft	Squat, ft	Speed Shown on Figure
American Spirit	UEX	?	?	?	9.0		UL	11.0 (13.0)	NM	7
Mary Gail	UEN	1,200	?	?	?		?	11.0 (13.0)	NM	8
Paul Leiway	DEX	1,410	?	?	?		8.5	11.0 (13.0)	NM	9
Marie Thompsen	UEN	3,200	?	?	?		UL	11.2 (13.2)	Sta 400 downstream = 0.3 Sta 50 downstream = 0.3 Forward thrust just past sill = 0.6 Reverse = 0.15	NM
David McAllister	DEX	3,200	?	111 × 30	?		8.5	11.8 (13.8)	NM	10
Louis Meeve	DEX	5,600	90" w/Kort Nozzles	140 × 48	9.0		8.5	12.1 (14.1)	Initial acceleration = 0.80 Underway before reaching sill = 0.25-0.65 Over sill = 0.20	11
William Pitt	DEX	1,700	Open Wheel	115 × 26	7-8.0		8-9.0	12.0 (14.0)	Initial acceleration = 0.15 Underway = 0.15	12
William H. Liggett	DEX	6,000	Kort Nozzles	145 × 48	10.0		8.5-9.0	11.8 (13.8)	Initial acceleration = 0.35 Underway before sill = 0.50 Over sill = 0.35 Past sill = 0.20	13
Omega	UEN	6,700	Kort Nozzles	150 × 47	10.0		9.0	11.8 (13.8)	Maximum = 0.10	NM
Capt. Brisco	UEN	5,600	?	155 × 48	?	Integrated 108 ft × 1,150 ft Loaded	?	11.8 (13.8)	NM	14
Louis Meeve	UEN	5,600	90" w/Kort Nozzles	140 × 48	9.0		9.0	10.2 (12.2)	Underway = 0.30 Hard reverse = 0.50	15
Bill, Jr.	DEX	1,130	Open Wheel	64 × 24	6.0		9.0	10.0 (12.0)	≤0.15	16

Note: ? = unknown; NM = no measurement.
* DEX = downbound exiting; UEX = upbound exiting; UEN = upbound entering.
** UL = unloaded; L = loaded.

Table 2

Individual Test Results, All Tows Loaded

Test No.	Direction	Draft ft	Depth Over Sill, ft	Propeller Speed, rpm, or Towing Test	Squat Over Lower Sill, ft: Bow of Barges	Squat Over Lower Sill, ft: Middle of Barges	Squat Over Lower Sill, ft: Bow of Towboat	Squat Over Lower Sill, ft: Stern of Towboat	With or Without Filling/ Emptying Flume
1	UEN	9.0	11.0	105	-0.24	-0.02	0.48	0.52	With
2	UEN			123	-0.06	0.26	0.50	0.74	
3	UEN			140	-0.08	0.18	0.58	1.06	
4	UEN			157	-0.04	0.06	0.68	0.96	
5	DEX			105	0.0	0.20	0.40	0.46	
6	DEX			123	0.04	0.12	0.26	0.56	
7	DEX			140	0.32	0.54	0.58	1.06	
8	DEX			157	0.30	0.38	0.64	1.33	
9	UEN		11.5	105	-0.22	0.10	0.24	0.52	
10	UEN			123	-0.28	0.08	0.34	0.84	
11	UEN			140	-0.12	-0.18	0.28	0.92	
12	UEN			157	-0.36	-0.36	0.25	1.04	
13	DEX			105	0.0	-0.06	0.18	0.32	
14	DEX			123	0.38	0.62	0.58	0.70	
15	DEX			140	0.20	0.46	0.62	0.82	
16	DEX			157	0.08	0.74	0.82	1.32	
17	UEN	9.5	11.0	105	-0.12	-0.12	0.24	0.74	
18	UEN			123	-0.20	0.0	0.30	0.82	
19	UEN			140	-0.34	-0.02	0.36	1.32	
20	UEN			157	-0.36	0.0	0.32	1.66	

(Continued)

Note: DEX = downbound exiting.
UEN = upbound entering.
CS = constant speed towing test (Plates 19-24. indicate various tow speeds tested).
NM = no measurement.
Negative value indicates rise above still water level.

Table 2 (Continued)

Test No.	Direction	Draft ft	Depth Over Sill, ft	Propeller Speed, rpm, or Towing Test	Squat Over Lower Sill, ft: Bow of Barges	Squat Over Lower Sill, ft: Middle of Barges	Squat Over Lower Sill, ft: Bow of Towboat	Squat Over Lower Sill, ft: Stern of Towboat	With or Without Filling/ Emptying Flume
21	DEX	9.5	11.0	105	-0.02	0.16	0.34	0.32	With
22	DEX			123	0.02	0.10	0.42	0.46	
23	DEX			140	0.06	0.24	0.44	0.98	
24	DEX			157	0.06	0.0	0.62	1.22	
25	UEN		11.5	105	-0.52	-0.26	0.30	0.68	
26	UEN			123	-0.40	-0.12	0.30	0.94	
27	UEN			140	-0.56	-0.20	0.38	1.20	
28	UEN			157	-0.54	0.02	0.72	1.38	
29	DEX			105	0.04	0.12	0.34	0.54	
30	DEX			123	-0.02	0.28	0.42	0.76	
31	DEX			140	0.16	0.42	0.56	0.82	
32	DEX			157	0.22	0.32	0.56	0.92	
33	UEN		12.0	105	-0.16	-0.24	0.18	0.62	
34	UEN			123	0.0	0.04	0.34	0.78	
35	UEN			140	0.08	0.12	0.42	0.88	
36	UEN			157	-0.30	-0.42	0.64	1.24	
37	DEX			105	0.18	0.16	0.32	0.45	
38	DEX			123	0.08	0.14	0.60	0.77	
39	DEX			140	-0.06	0.24	0.62	0.65	
40	DEX			157	0.18	0.32	0.30	1.23	
41	UEN	10.0	11.5	105	-0.36	-0.22	0.28	0.70	
42	UEN			123	-0.58	-0.24	0.34	1.20	
43	UEN			140	-0.46	-0.34	0.46	1.30	
44	UEN			157	-0.44	-0.24	0.32	1.50	
45	DEX			105	0.10	0.18	0.18	0.34	

(Continued)

(Sheet 2 of 4)

Table 2 (Continued)

Test No.	Direction	Draft ft	Depth Over Sill, ft	Propeller Speed, rpm, or Towing Test	Squat Over Lower Sill, ft: Bow of Barges	Middle of Barges	Bow of Towboat	Stern of Towboat	With or Without Filling/ Emptying Flume
46	DEX	10.0	11.5	123	0.04	0.14	0.28	0.76	With
47	DEX			140	-0.02	0.24	0.52	0.76	
48	DEX			157	0.02	0.42	0.44	0.94	
49	UEN		12.0	105	-0.50	-0.21	-0.09	0.71	
50	UEN			123	-0.42	-0.19	0.05	0.75	
51	UEN			140	-0.40	-0.27	0.05	0.87	
52	UEN			157	-0.40	-0.15	0.09	1.51	
53	DEX			105	0.14	0.08	0.40	0.56	
54	DEX			123	0.06	0.24	0.48	0.88	
55	DEX			140	0.02	0.30	0.62	1.14	
56	DEX			157	0.28	0.54	0.86	1.30	
57	UEN		12.5	105	-0.30	0.22	0.32	0.82	
58	UEN			123	-0.36	0.18	0.42	1.10	
59	UEN			140	-0.14	0.38	0.62	0.92	
60	UEN			157	-0.70	-0.22	0.52	1.10	
61	DEX			105	-0.06	0.22	0.32	0.44	
62	DEX			123	0.16	0.32	0.38	0.49	
63	DEX			140	0.18	0.38	0.60	0.75	
64	DEX			157	0.12	0.50	0.78	1.15	
65	UEN		11.5	CS	NM	-0.12	0.0	0.0	
66	UEN			CS	NM	-0.42	0.06	0.06	
67	UEN			CS	NM	-0.62	0.04	0.08	
68	DEX			CS	NM	0.12	0.12	0.0	
69	DEX			CS	NM	0.34	0.86	0.60	
70	DEX			CS	NM	0.70	1.42	2.00	

(Continued)

Table 2 (Concluded)

Test No.	Direction	Draft ft	Depth Over Sill, ft	Propeller Speed, rpm, or Towing Test	Squat Over Lower Sill, ft: Bow of Barges	Middle of Barges	Bow of Towboat	Stern of Towboat	With or Without Filling/ Emptying Flume
71	UEN	10.0	12.0	CS	NM	-0.24	0.12	0.06	With
72	UEN			CS	NM	-0.40	0.08	0.12	
73	UEN			CS	NM	-0.60	0.10	0.06	
74	DEX			CS	NM	0.14	0.14	-0.04	
75	DEX			CS	NM	0.48	1.02	0.44	
76	DEX			CS	NM	0.74	1.54	1.30	
77	UEN		12.5	CS	NM	-0.38	0.08	0.02	
78	UEN			CS	NM	-0.30	0.16	0.08	
79	UEN			CS	NM	-0.60	0.12	0.06	
80	DEX			CS	NM	0.10	0.10	0.0	
81	DEX			CS	NM	0.36	0.66	0.22	
82	DEX			CS	NM	0.56	1.48	1.10	
83	UEN	9.0	11.0	105	-0.04	0.10	0.24	0.80	Without
84	UEN			105	-0.58	-0.14	0.24	0.66	
85	UEN			123	-0.40	0.10	0.16	0.90	
86	UEN			123	-0.42	0.14	0.28	0.88	
87	UEN			140	-0.36	0.22	0.40	1.38	
88	UEN			140	-0.12	0.22	0.24	1.06	
89	UEN			157	-0.66	0.16	0.28	1.42	
90	UEN			157	-0.62	0.20	0.14	1.64	
91	DEX			105	-0.24	0.08	0.24	0.30	
92	DEX			105	-0.18	0.16	0.16	0.30	
93	DEX			123	-0.22	0.18	0.42	0.38	
94	DEX			123	-0.26	0.22	0.30	0.48	
95	DEX			140	-0.10	0.26	0.42	0.48	
96	DEX			140	-0.10	0.26	0.36	0.42	
97	DEX			157	0.06	0.14	0.56	1.10	
98	DEX			157	-0.08	0.42	0.56	0.66	

(Sheet 4 of 4)

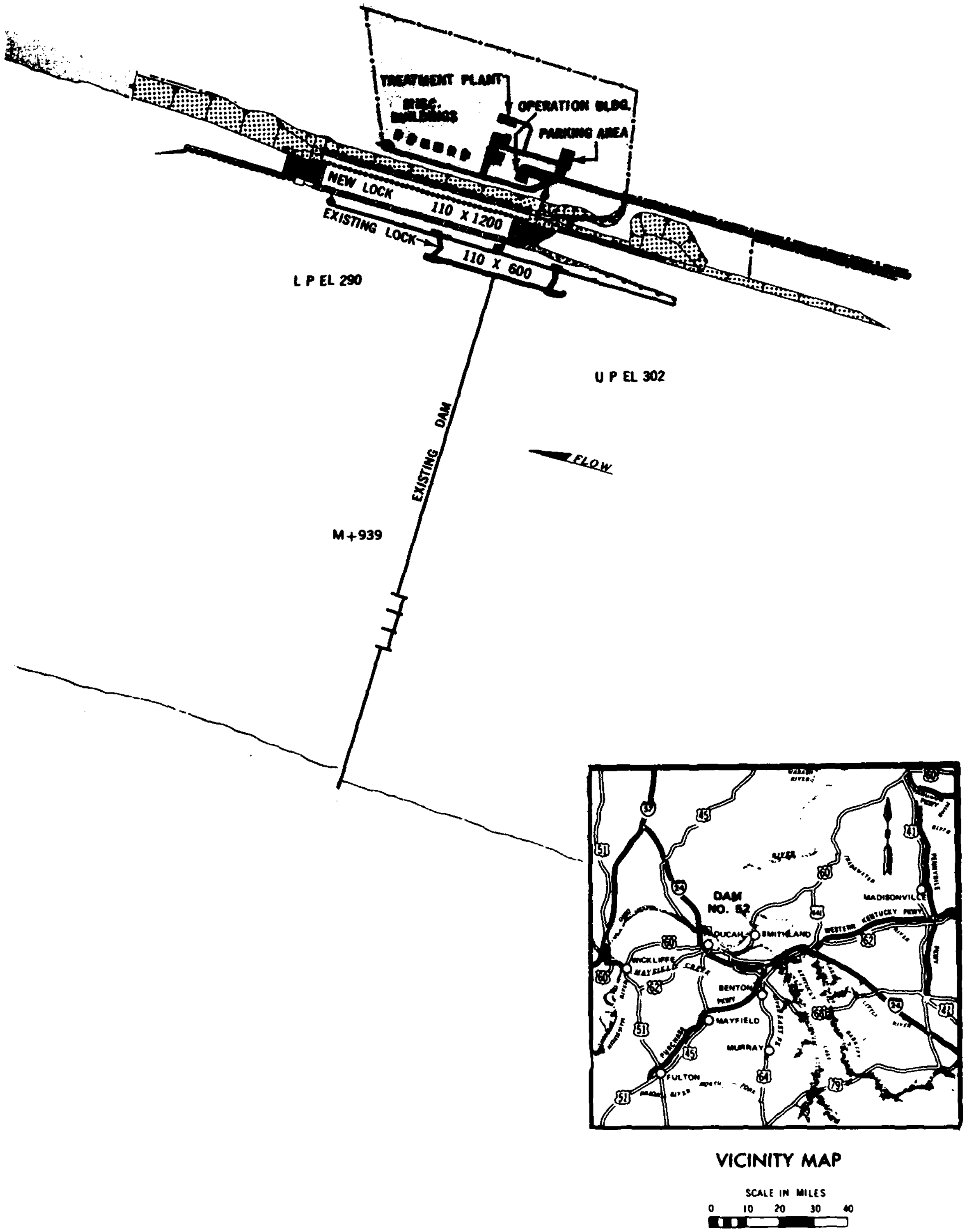


Figure 1. Ohio River Locks and Dam 52

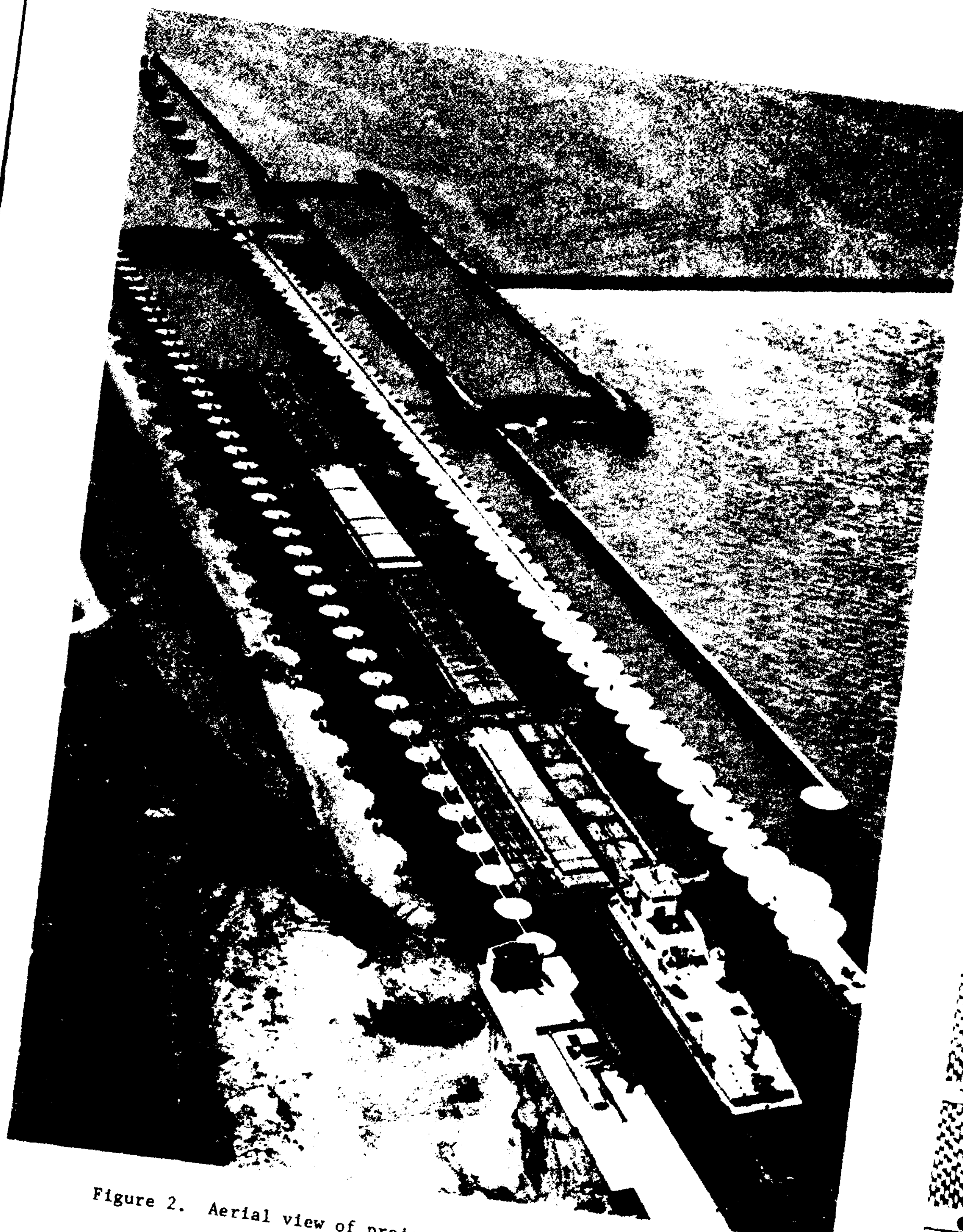


Figure 2. Aerial view of project, upbound tow entering lock

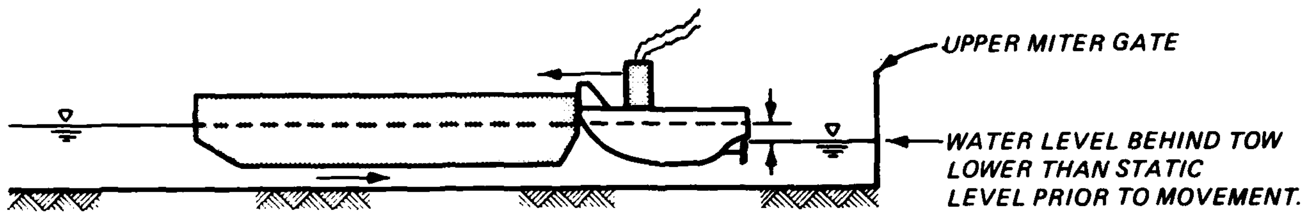


Figure 3. Piston squat

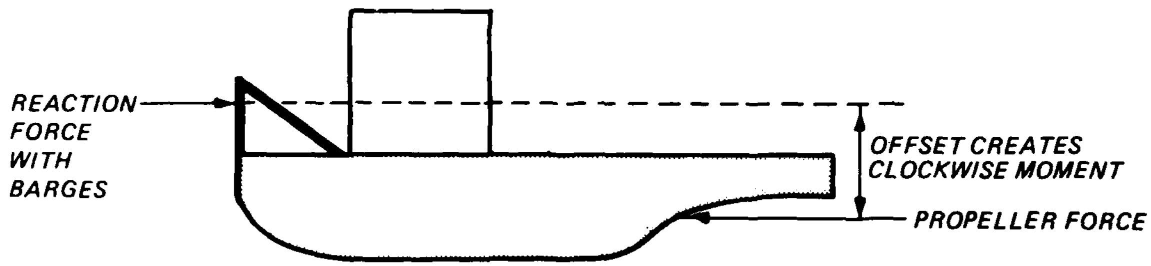


Figure 4. Moment squat

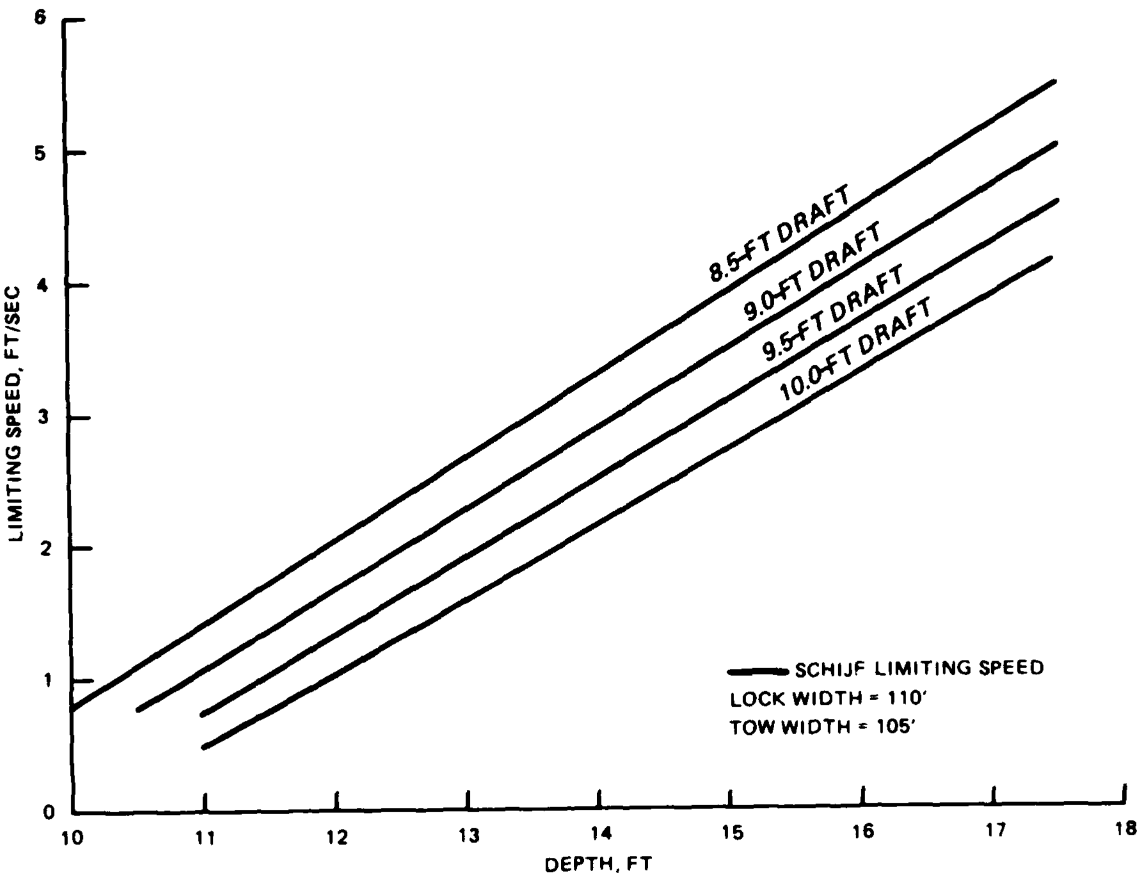
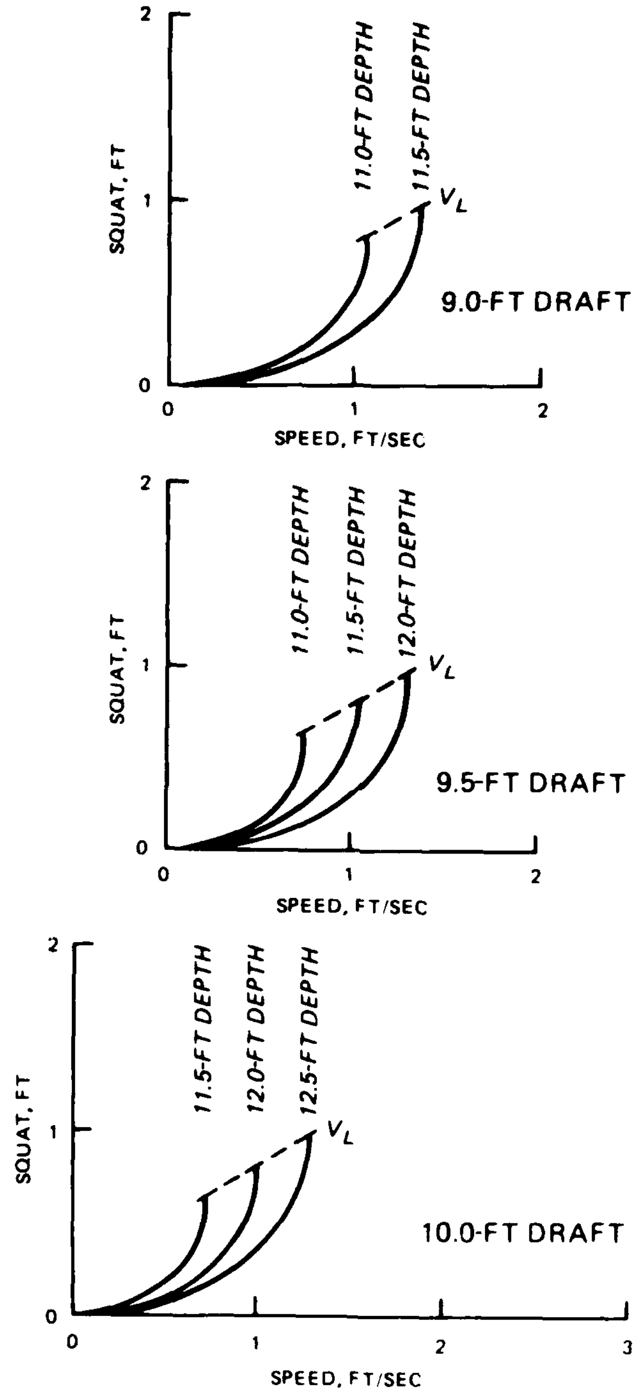


Figure 5. Jansen and Schijf's limiting speed



NOTE V_L = SCHIJF'S LIMITING SPEED

Figure 6. Squat based on Jansen and Schijf's method

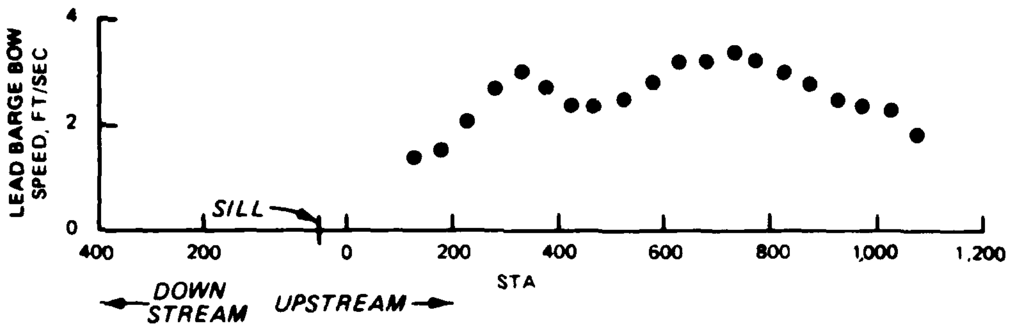


Figure 7. Tow speed, *American Spirit*, upbound exiting

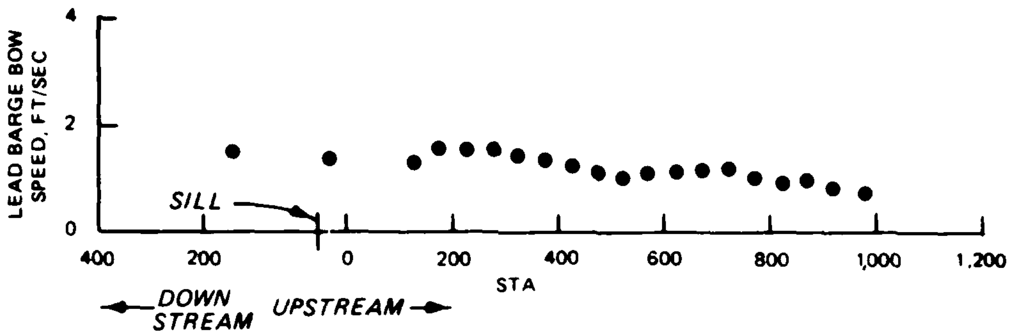


Figure 8. Tow speed, *Mary Gail*, upbound entering

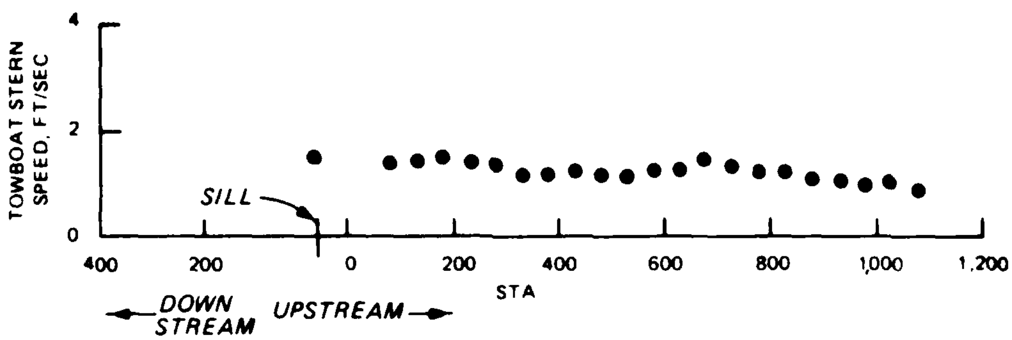


Figure 9. Tow speed, *Paul Legeay*, downbound exiting

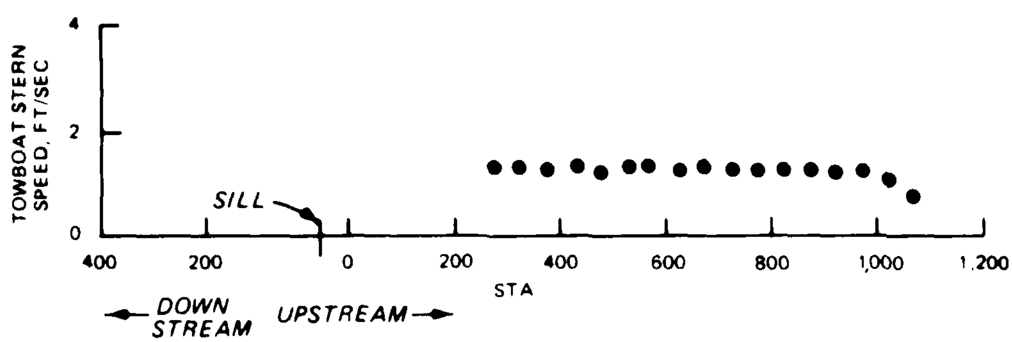


Figure 10. Tow speed, *David McAllister*, downbound exiting

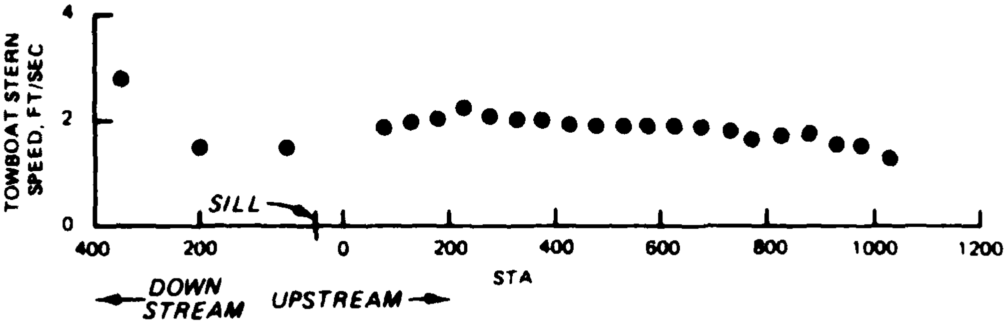


Figure 11. Tow speed, *Louis Meece*, downbound exiting

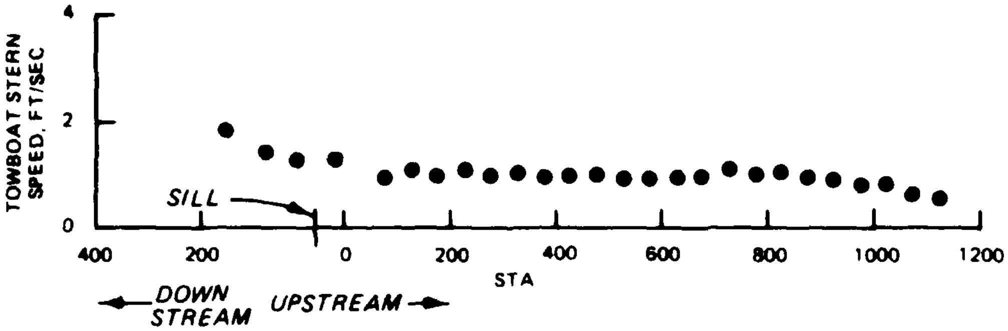


Figure 12. Tow speed, *William Pitt*, downbound exiting

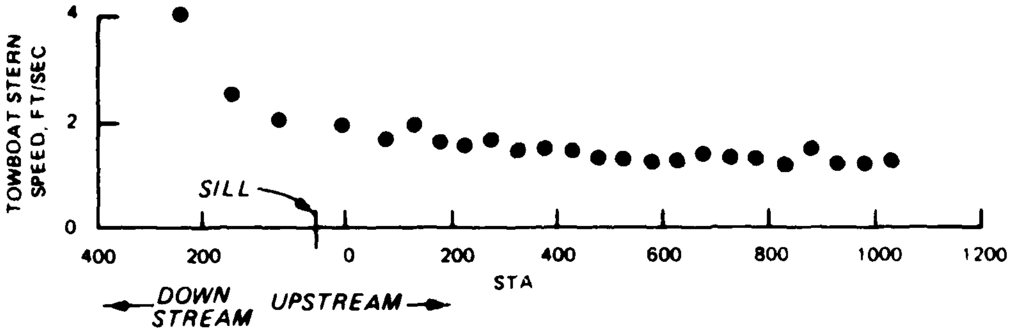


Figure 13. Tow speed, *William H. Liggett*, downbound exiting

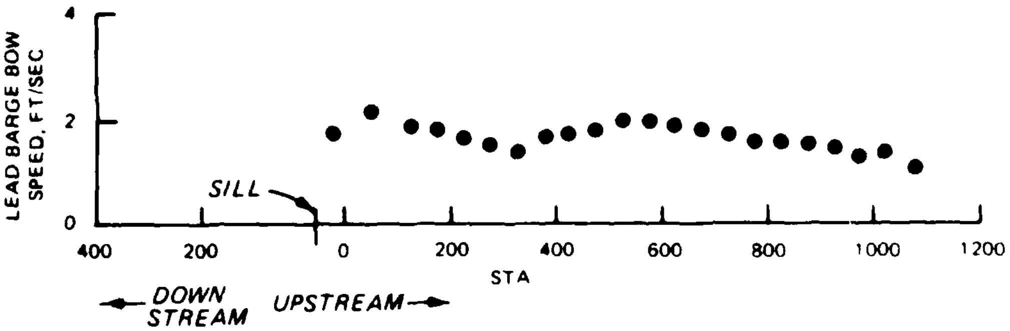


Figure 14. Tow speed, *[illegible]t. Bris[illegible]*, upbound entering

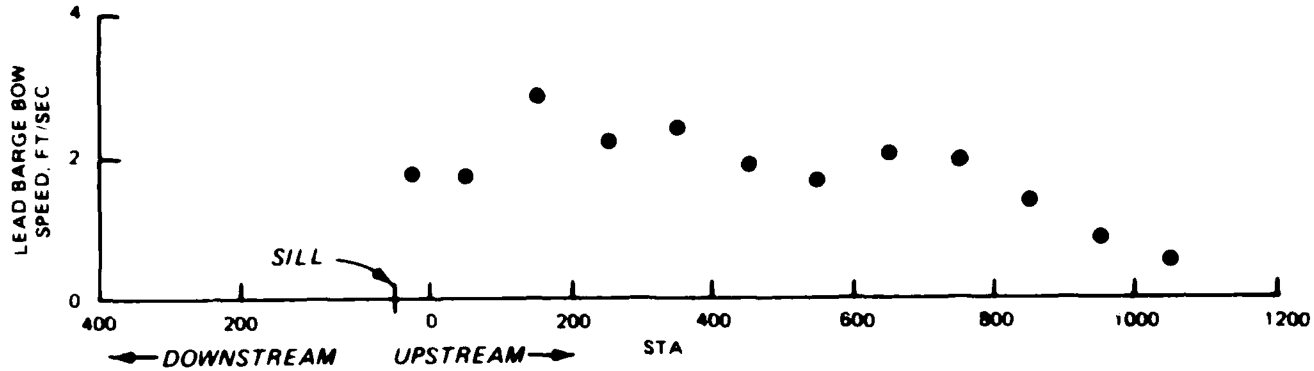


Figure 15. Tow speed, *Louis Meece*, upbound entering

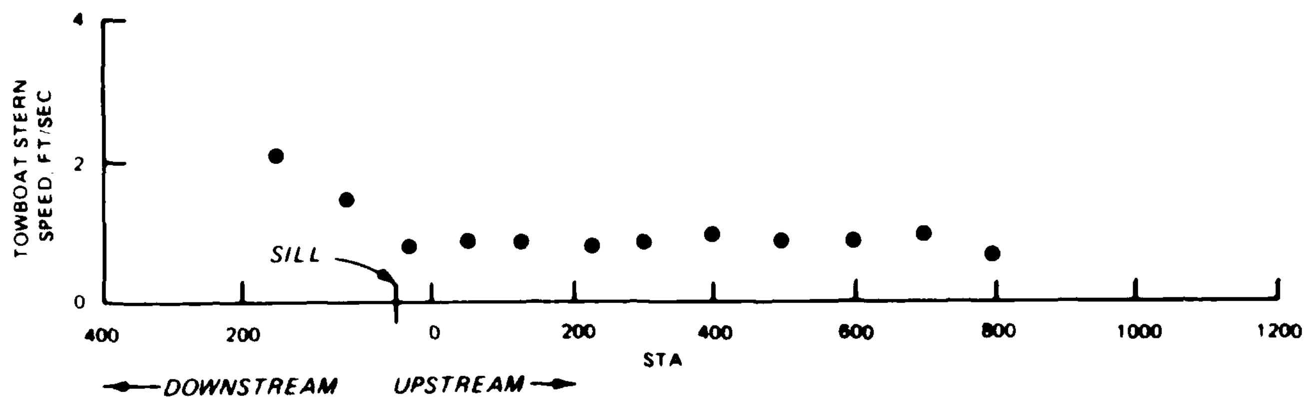
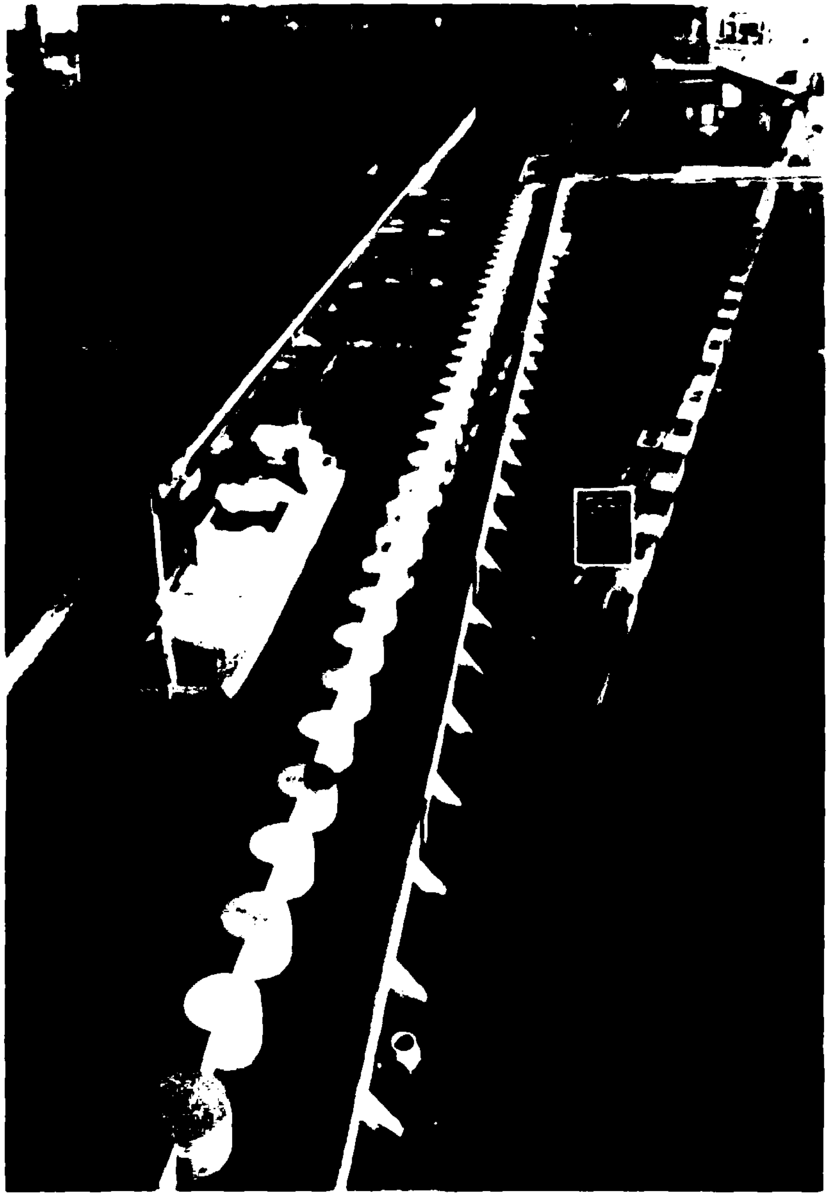


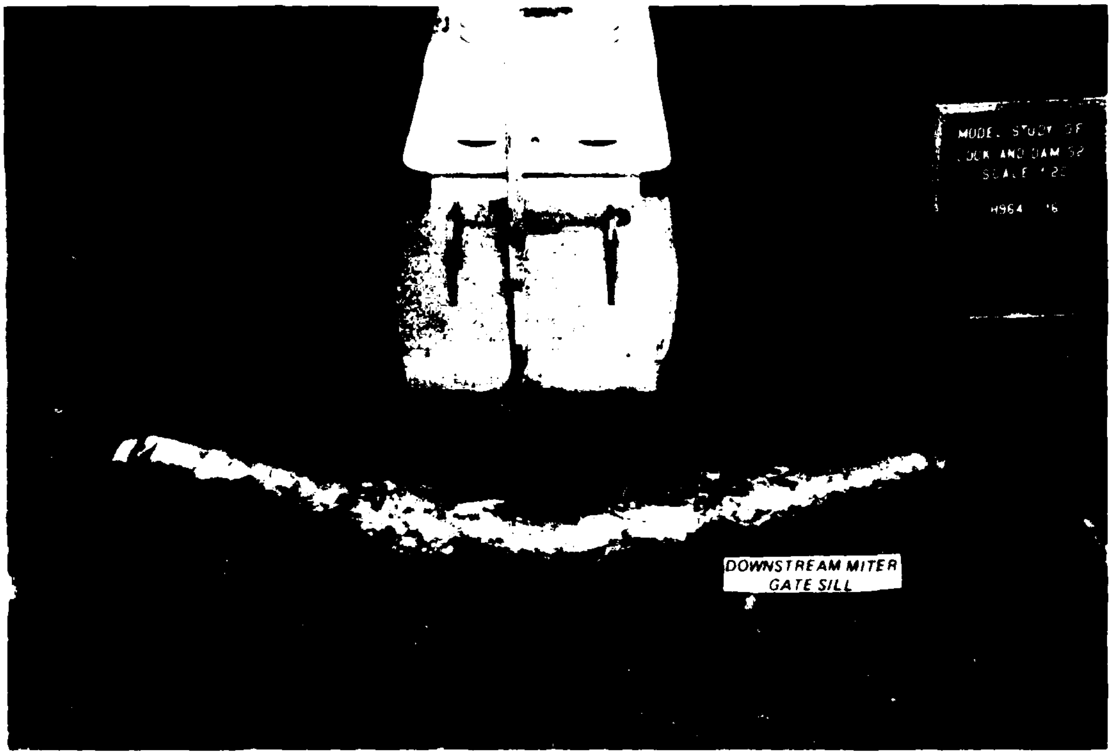
Figure 16. Tow speed, *Bill, Jr.*, downbound exiting



a. Downbound exiting tow

b. Upbound entering tow

Figure 17. 1:20-scale model, 1,200-ft temporary lock



a. Stern of towboat passing over lower sill

b. Side view of towboat passing over 1-ft-high lower sill

Figure 18. Lower miter gate sill

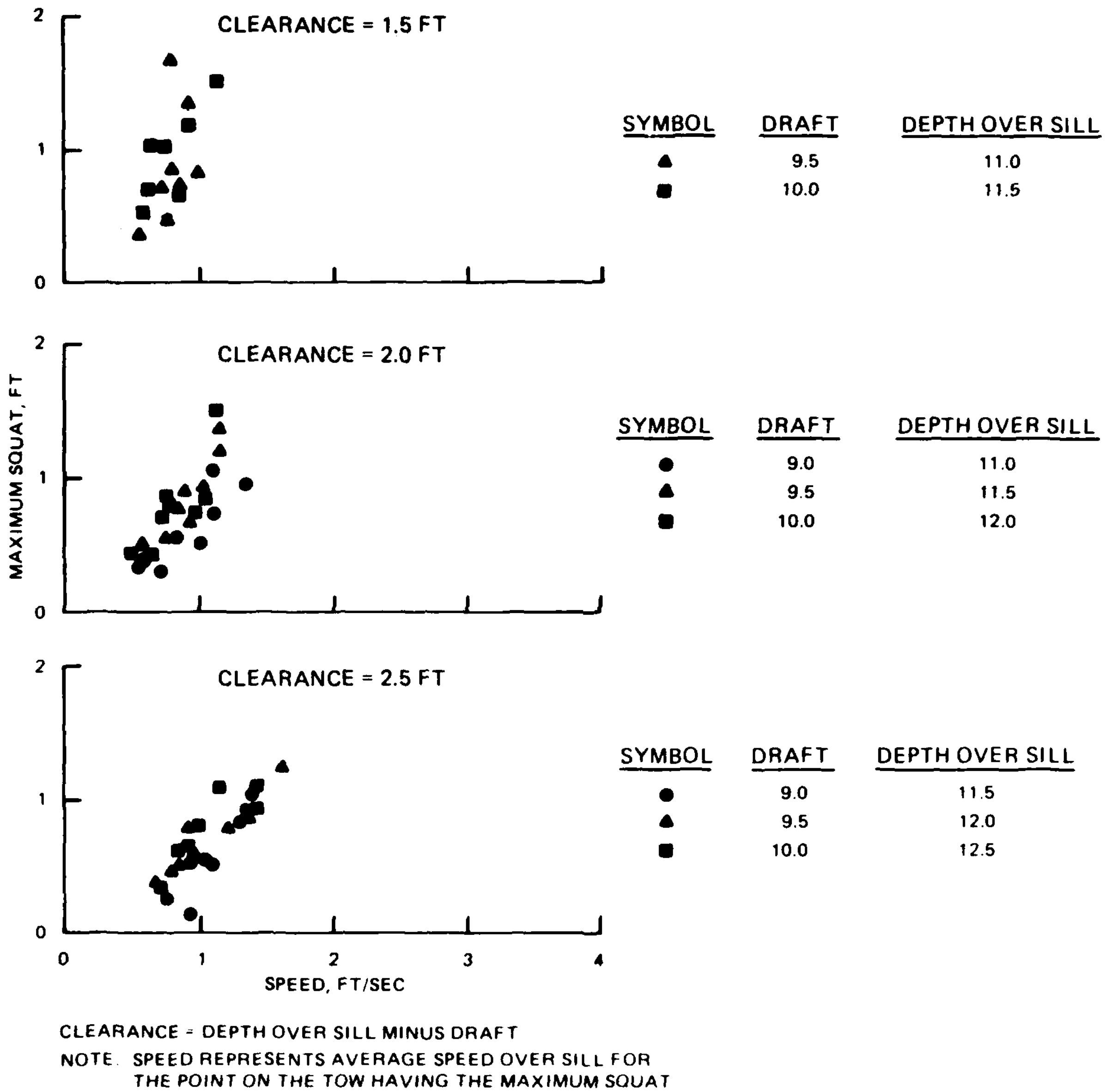


Figure 19. Maximum squat versus tow speed for entering loaded self-propelled tow

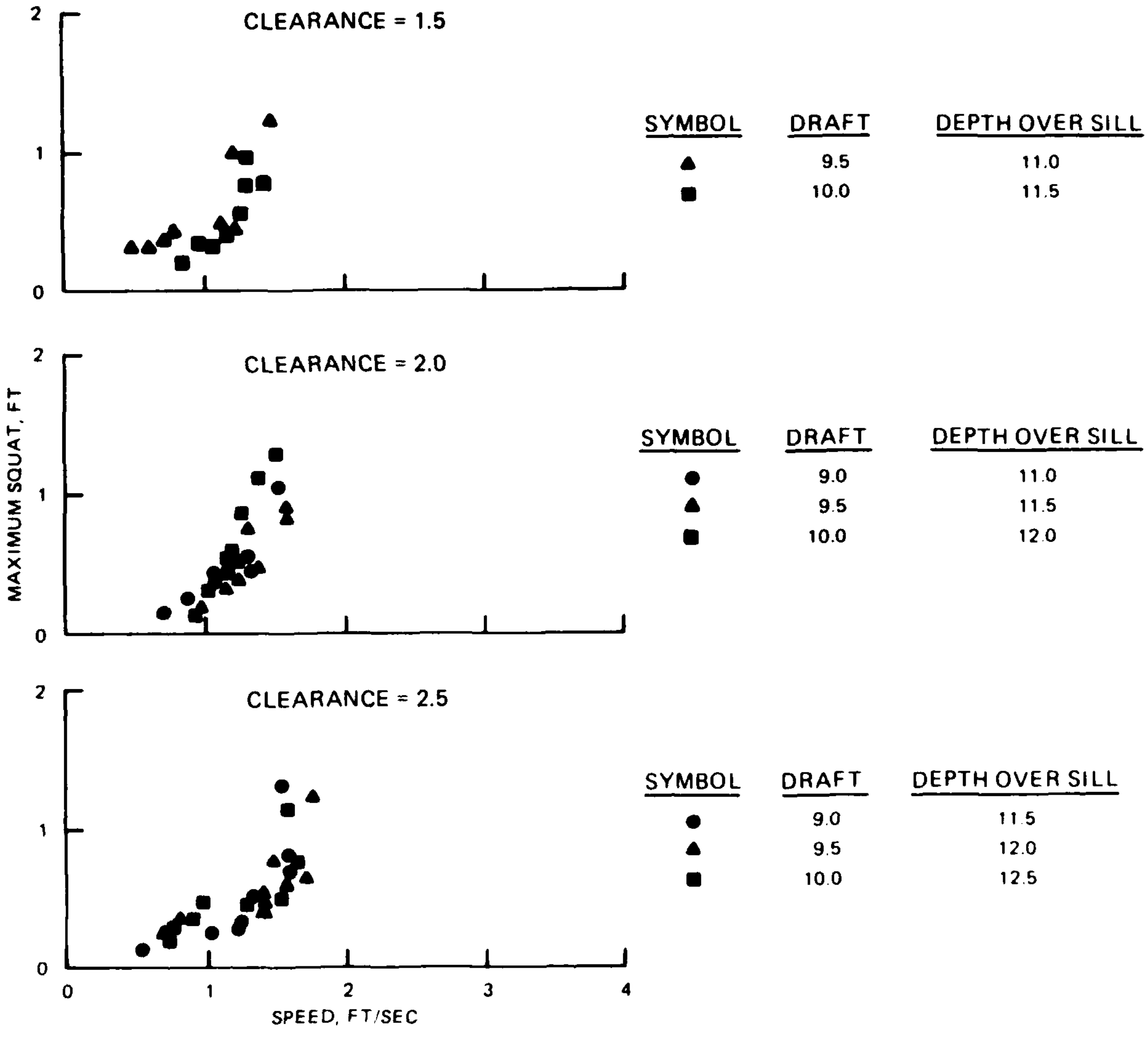


Figure 20. Maximum squat versus tow speed for exiting loaded self-propelled tow

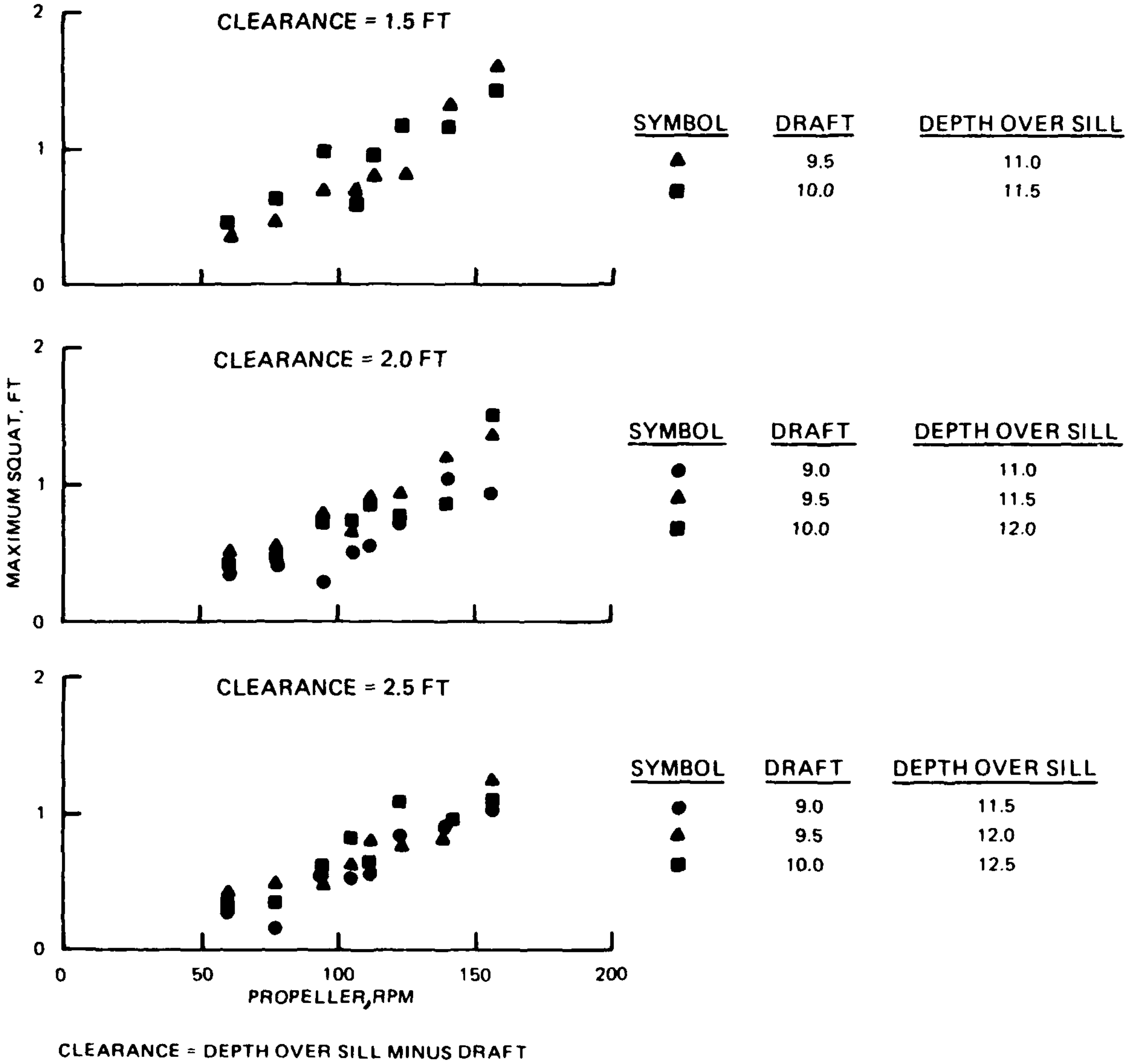


Figure 21. Maximum squat versus propeller speed for entering loaded self-propelled tow

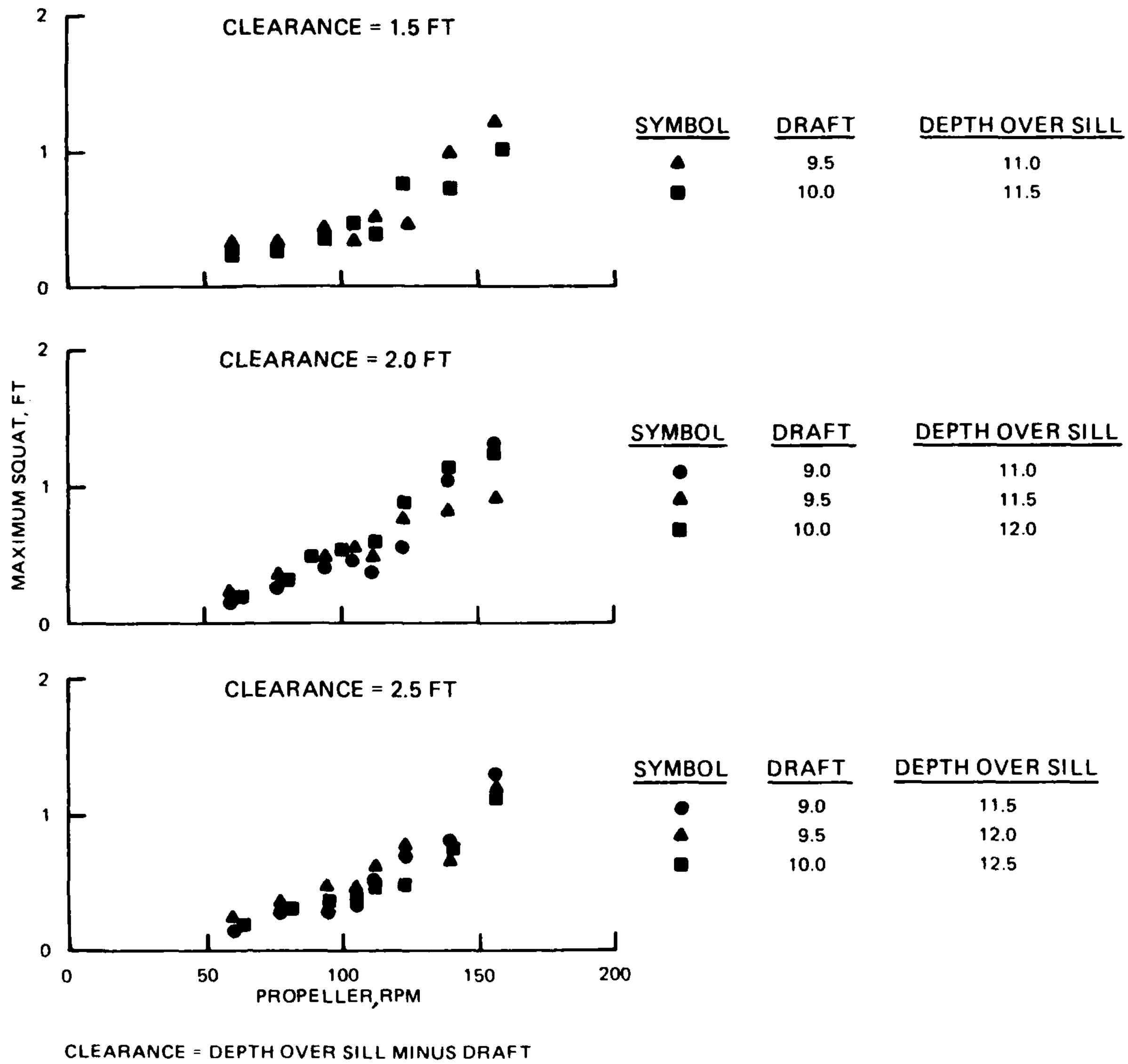


Figure 22. Maximum squat versus propeller speed for exiting loaded self-propelled tow

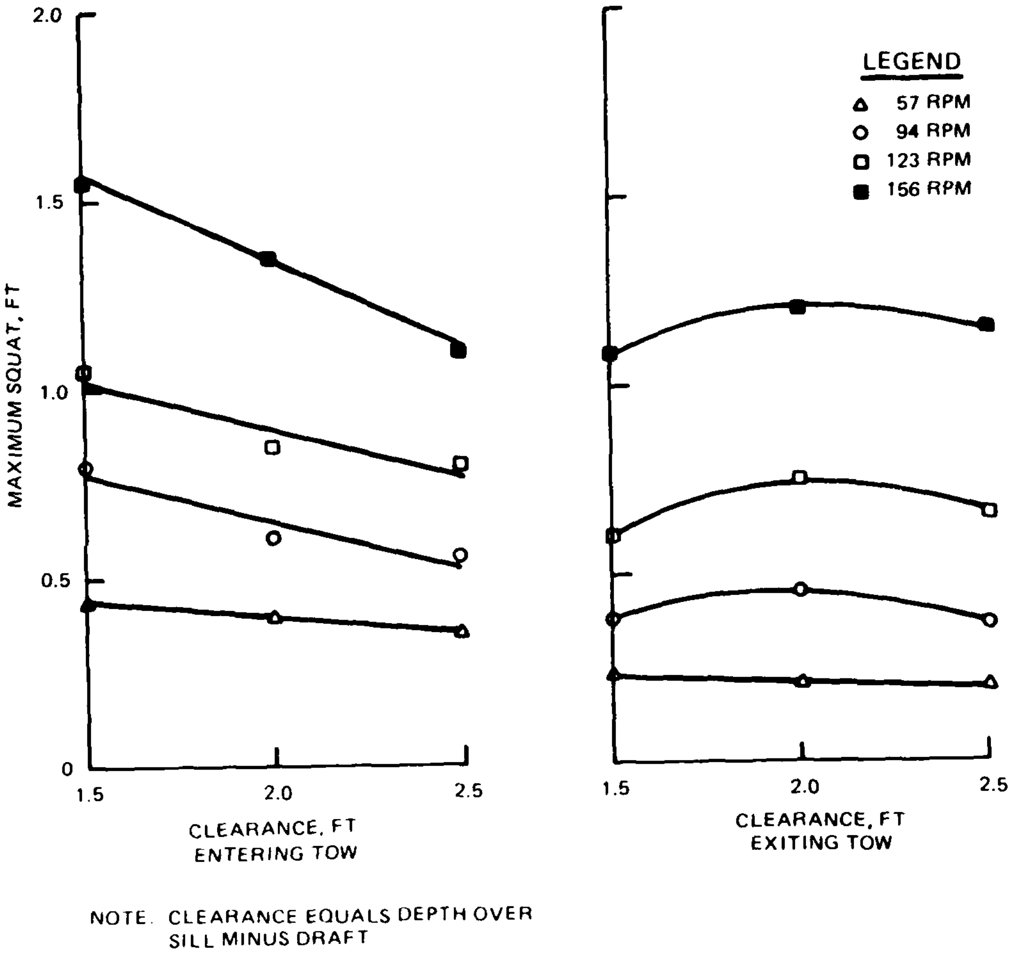


Figure 23. Maximum squat versus clearance versus propeller speed, entering and exiting loaded self-propelled tows

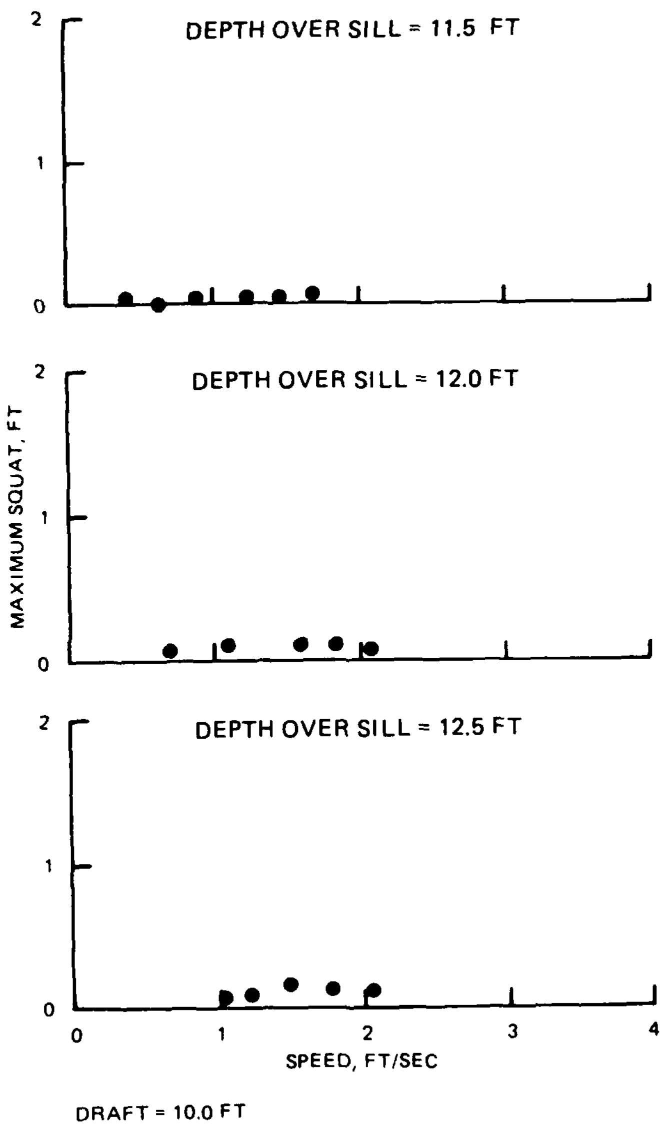


Figure 24. Maximum squat versus constant tow speed for entering loaded tow being pulled by towing mechanism

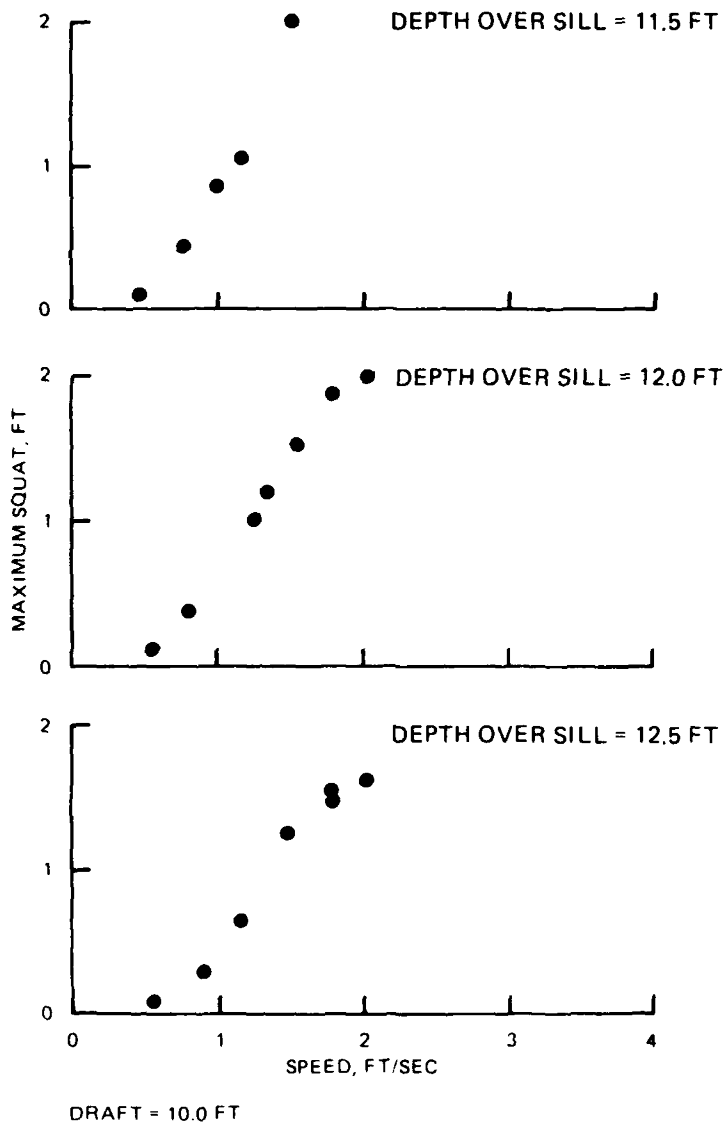


Figure 25. Maximum squat versus constant tow speed for exiting loaded tow being pulled by towing mechanism

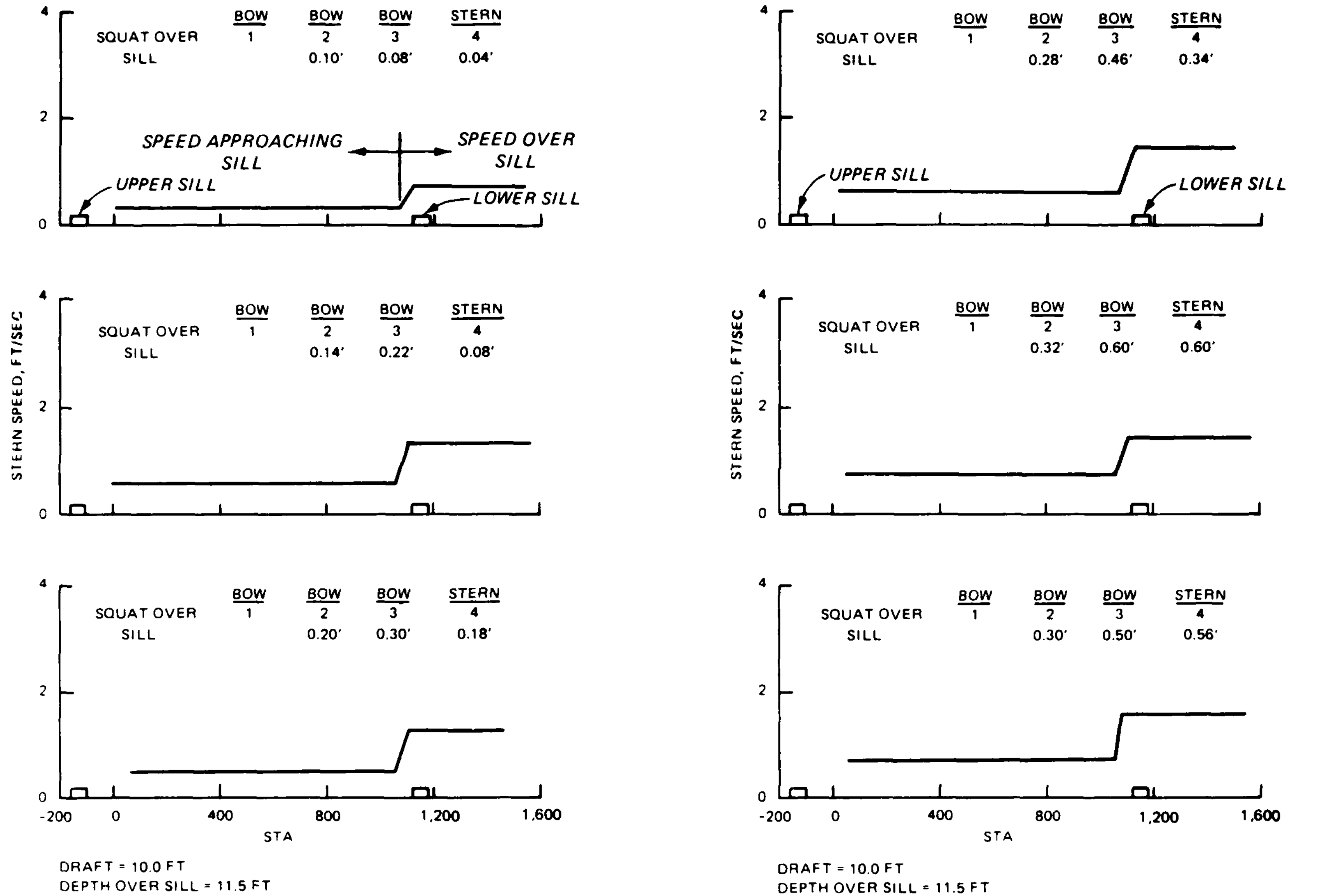


Figure 26. Variable speed test using towing mechanism to pull exiting loaded tow

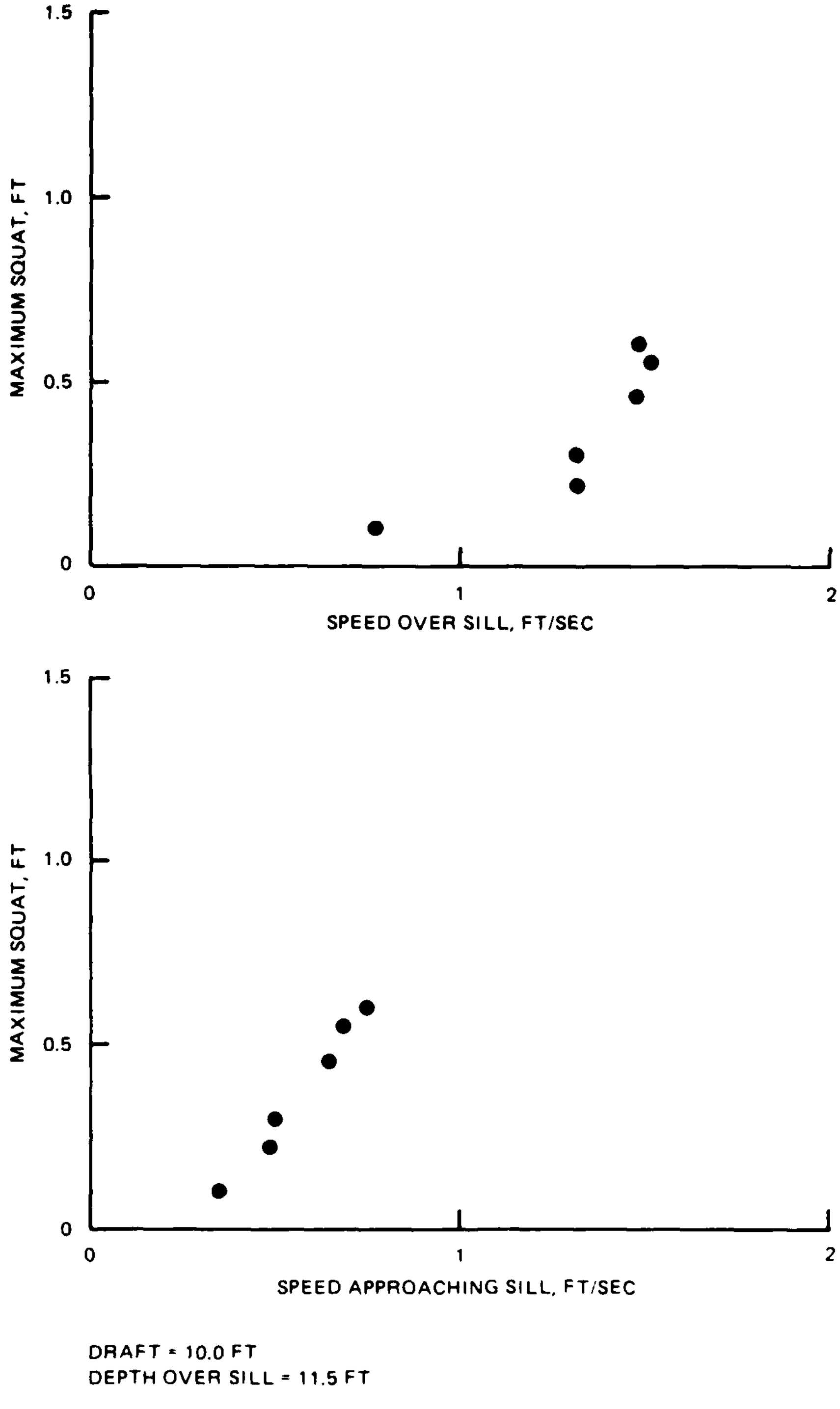


Figure 27. Summary of variable speed towing tests for exiting loaded tow

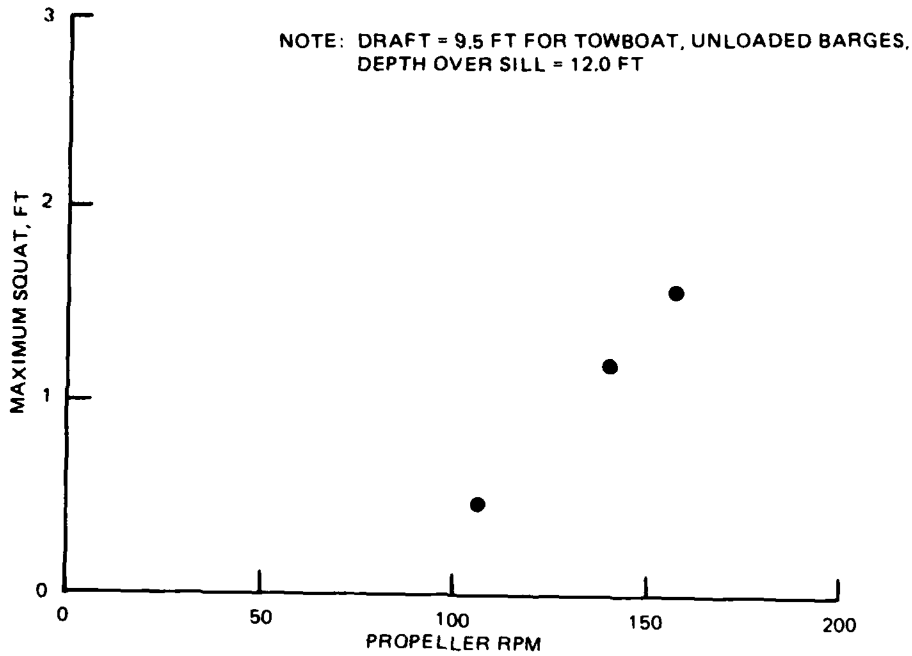


Figure 28. Maximum squat versus propeller speed for exiting unloaded self-propelled tow

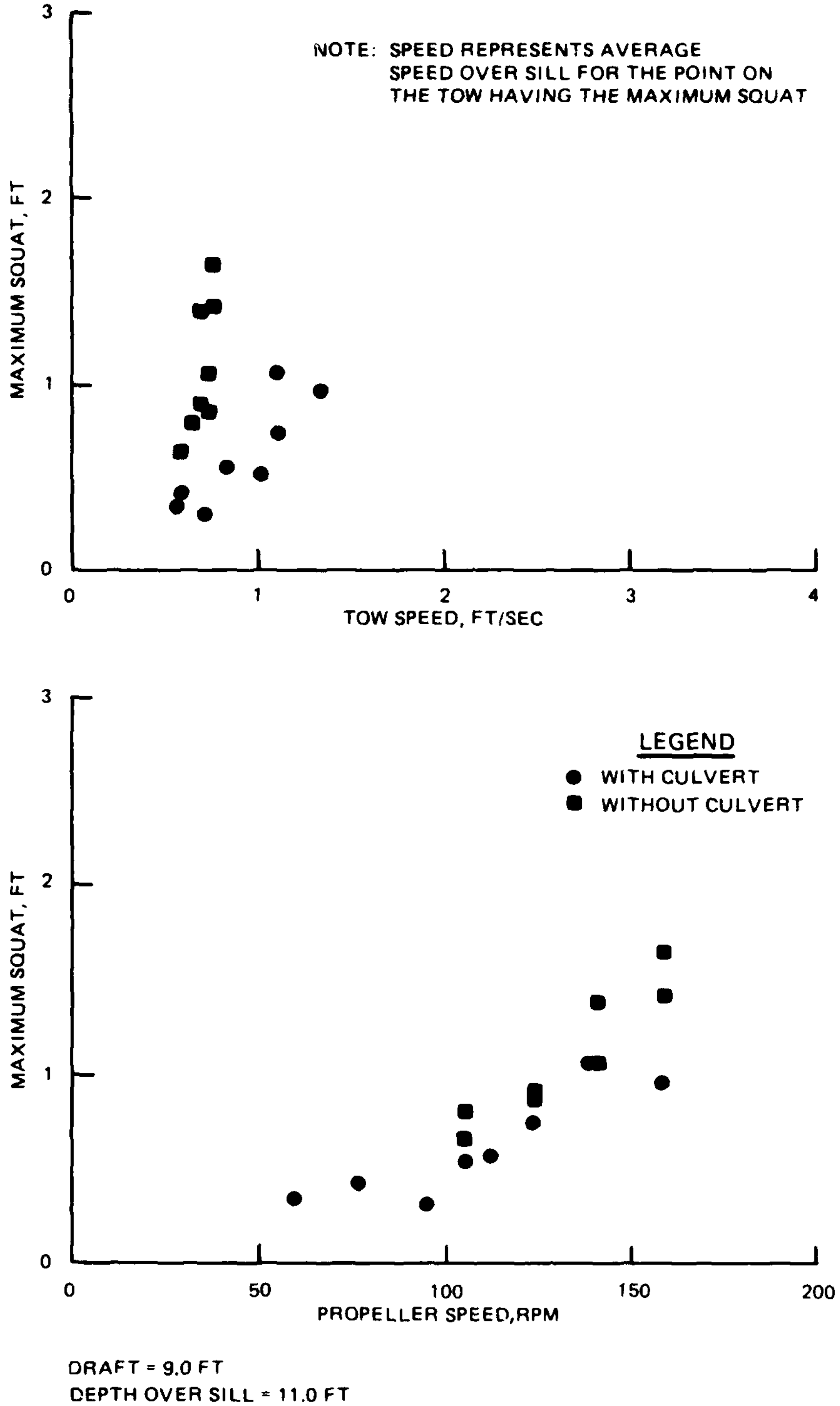


Figure 29. Comparison of tests with and without filling/emptying culvert for entering tows

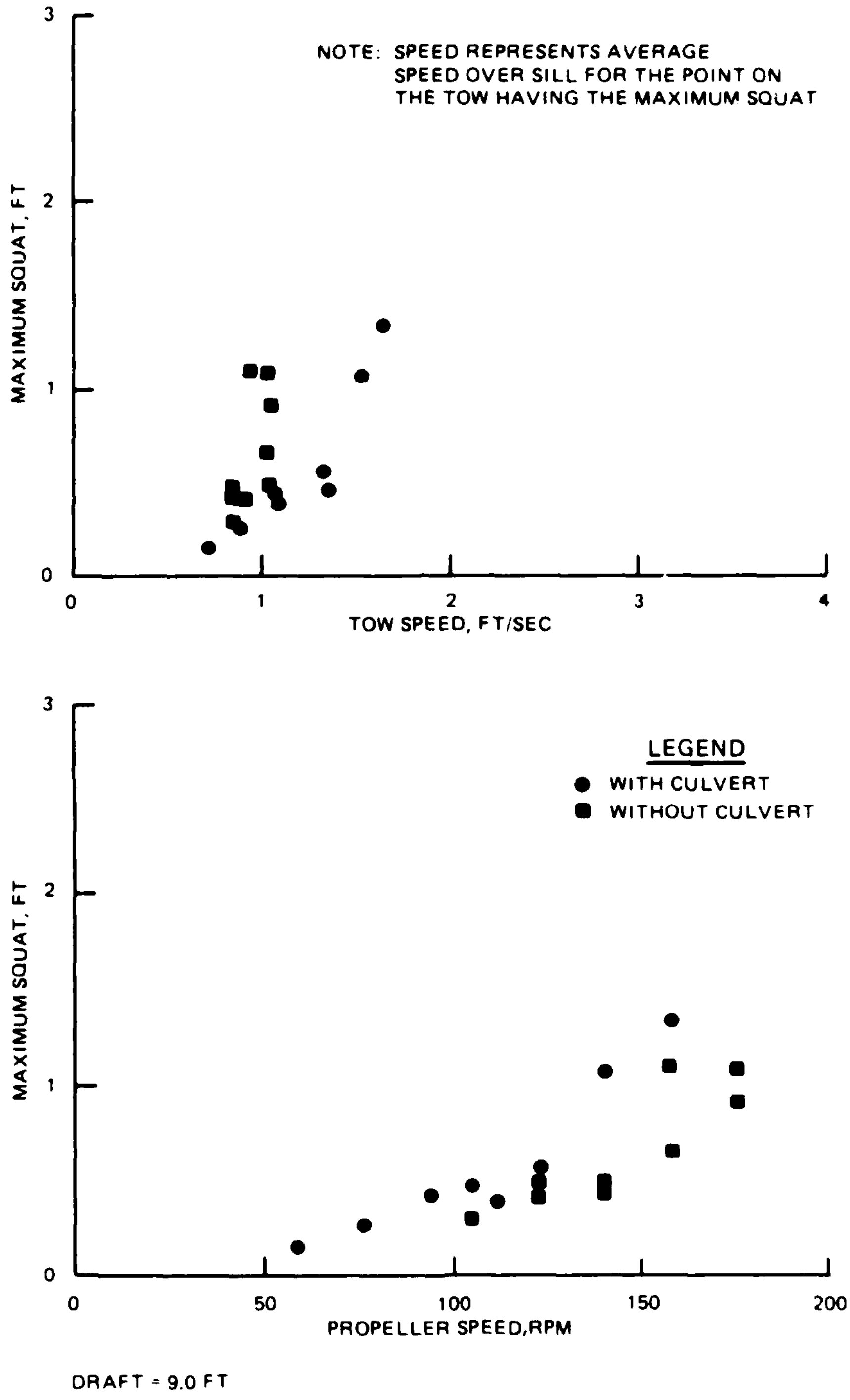
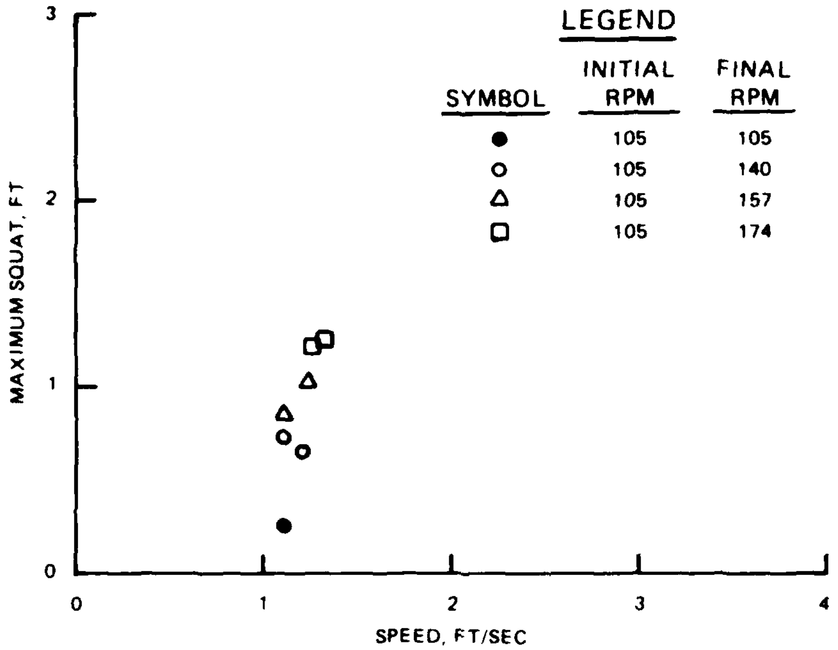


Figure 30. Comparison of tests with and without filling/emptying culvert for exiting tows



DRAFT = 9 FT
DEPTH OVER SILL = 12 FT

NOTE. SPEED REPRESENTS AVERAGE SPEED OVER SILL FOR THE POINT ON THE TOW HAVING THE MAXIMUM SQUAT. THESE TESTS WERE CONDUCTED WITHOUT THE LOCK EMPTYING CULVERT. PROPELLER SPEED INCREASED AS TOWBOAT BOW PASSED OVER LOWER SILL

Figure 31. Maximum squat versus tow speed for acceleration over sill for loaded exiting tow

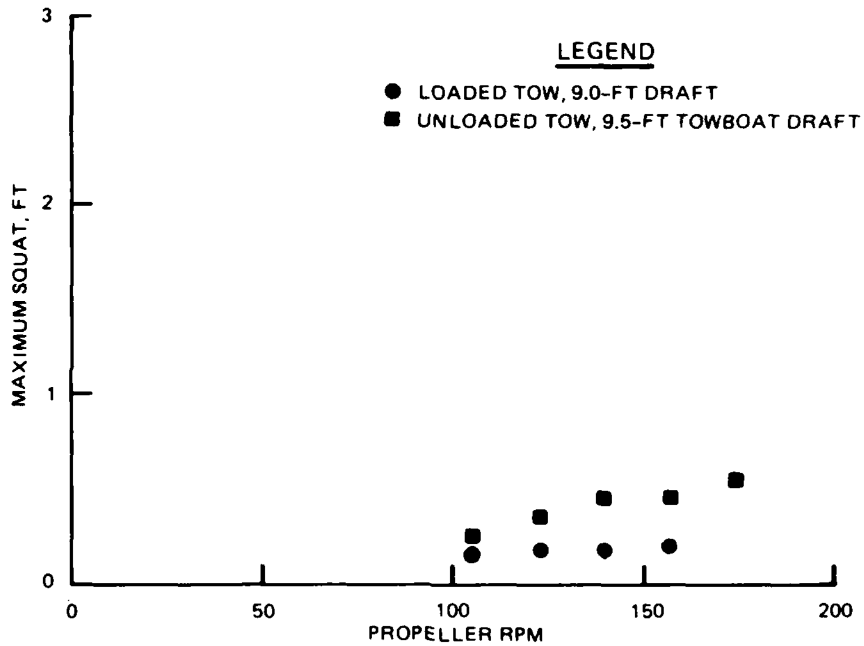
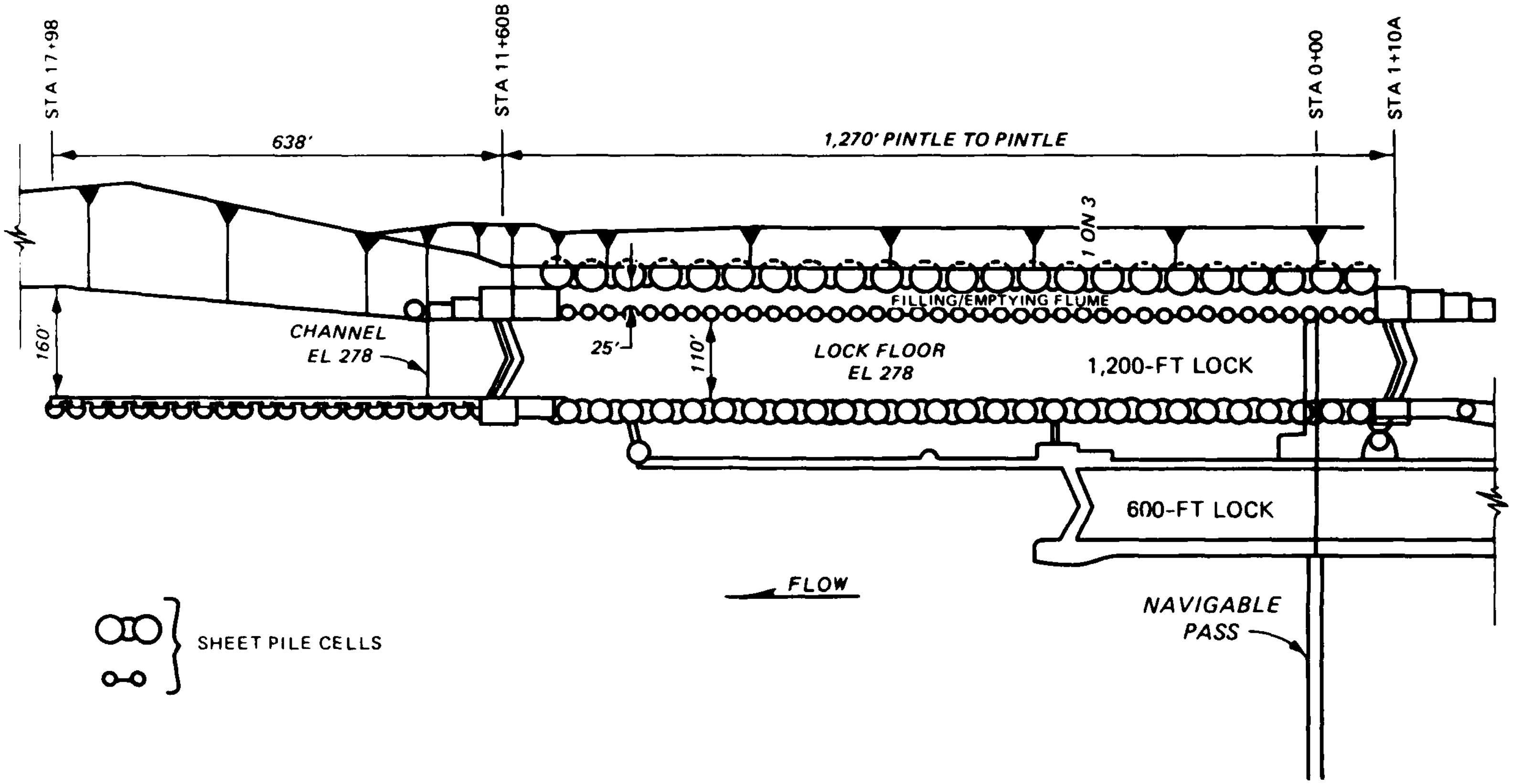
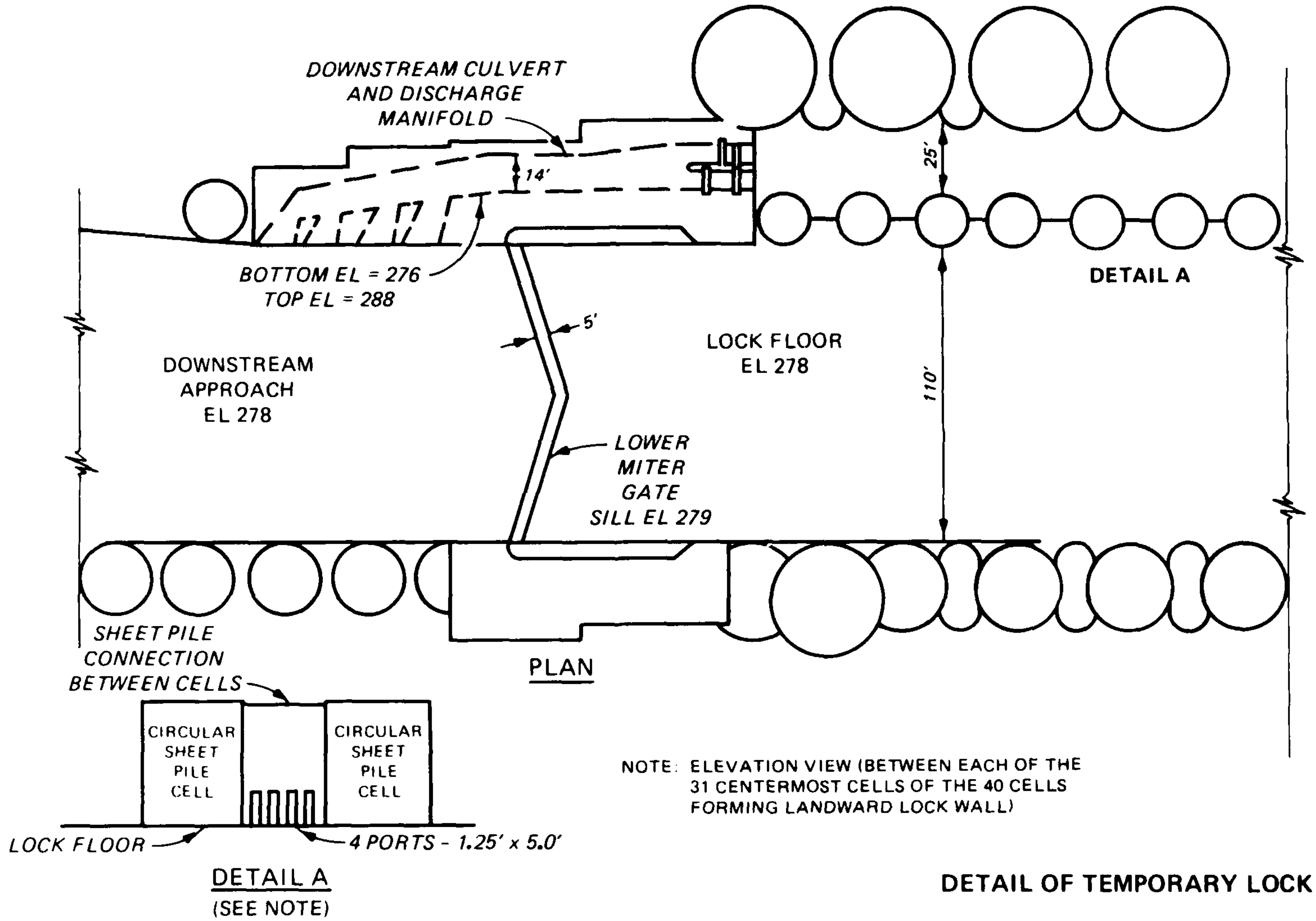


Figure 32. Moment squat tests, deep water

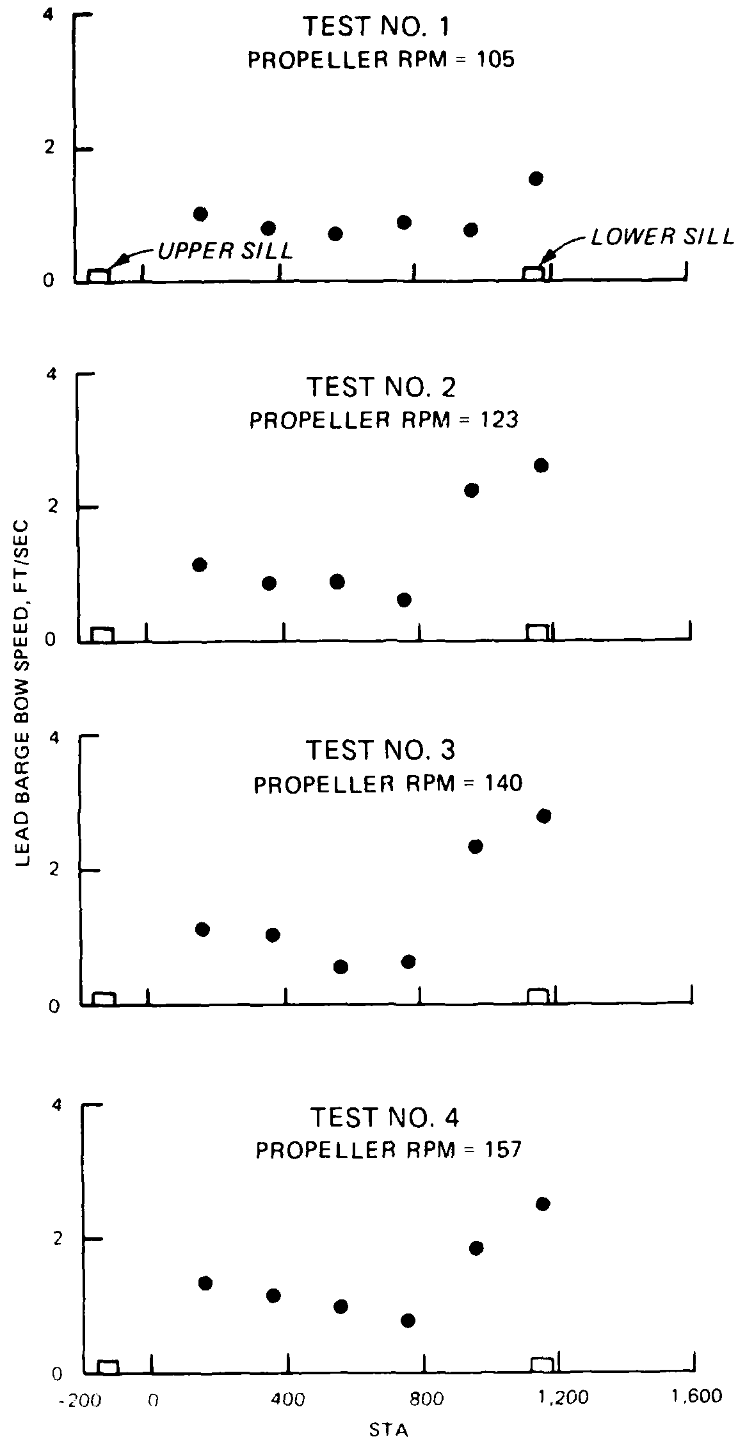


GENERAL PLAN OF
TEMPORARY LOCK

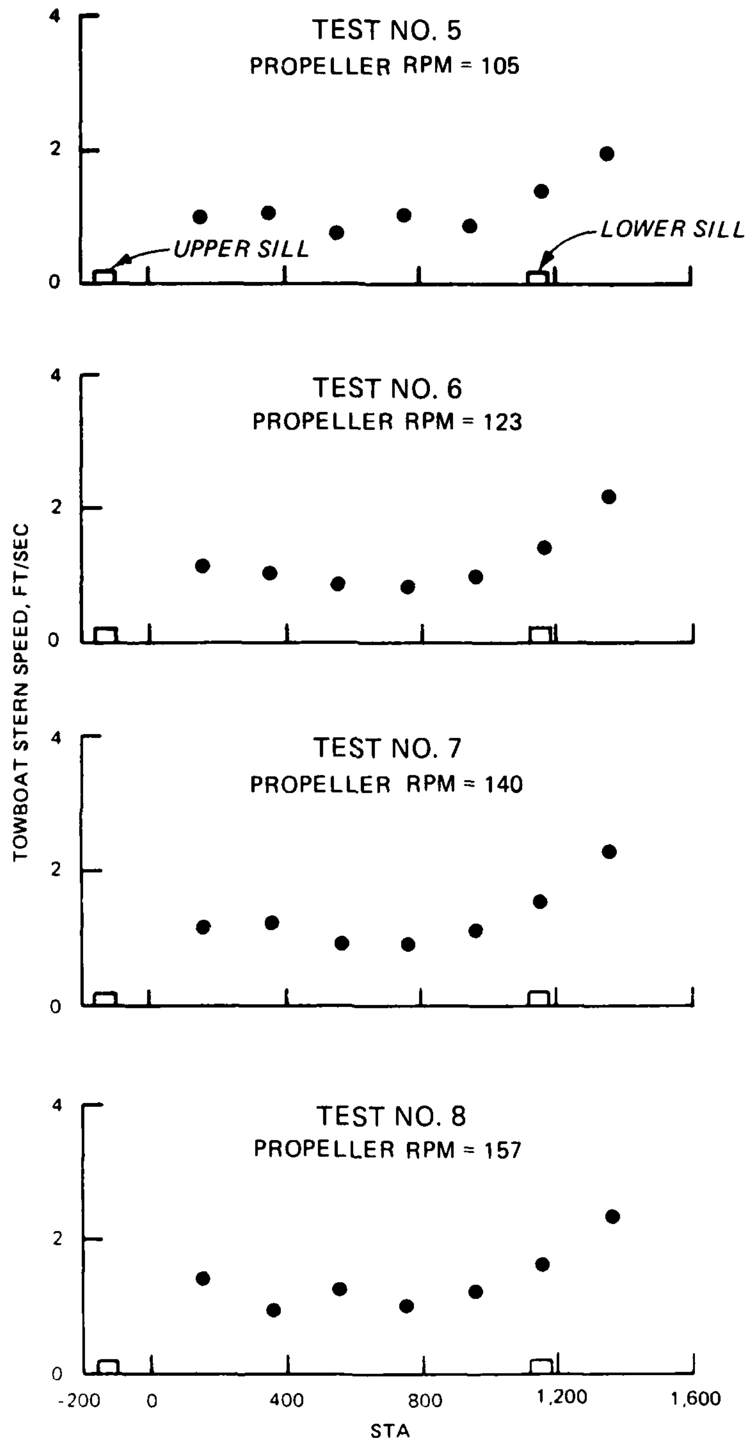


DETAIL OF TEMPORARY LOCK

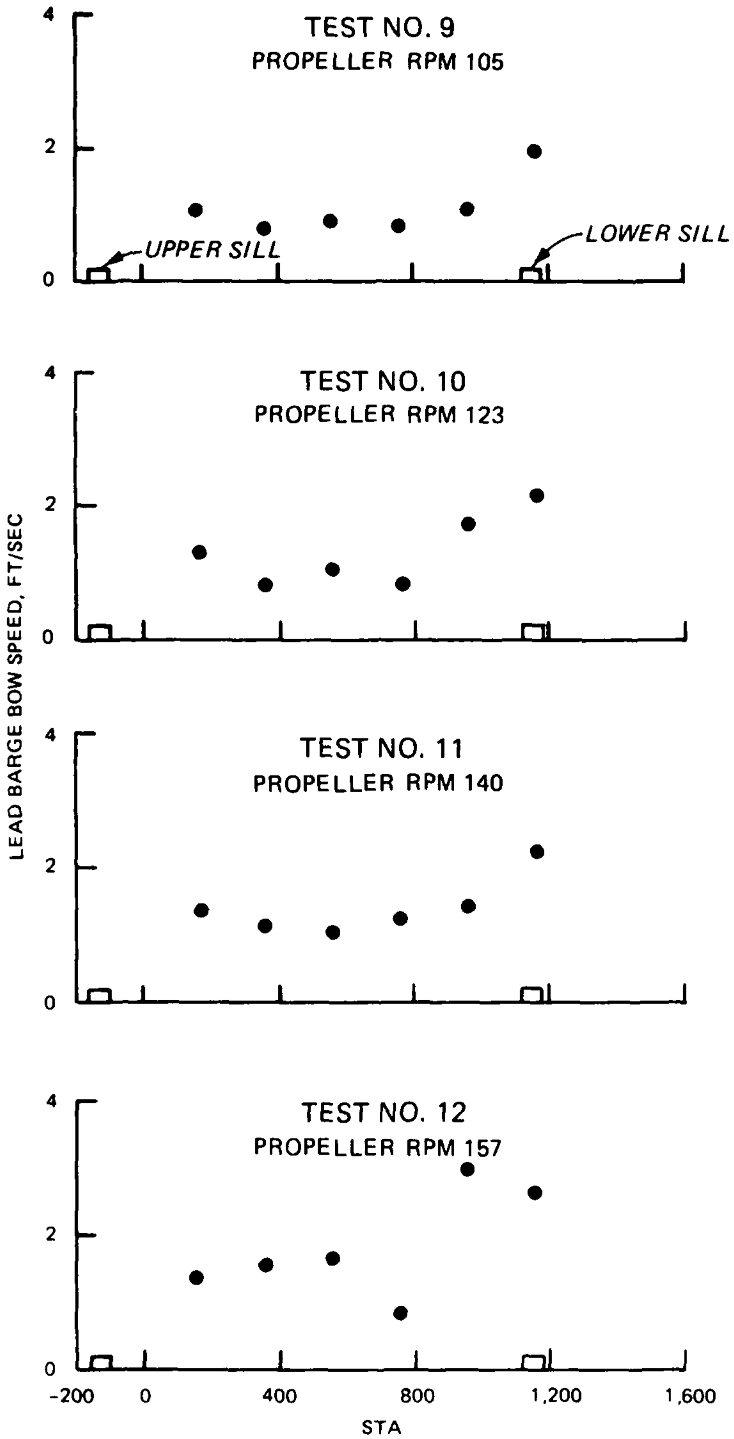
PLATE 2



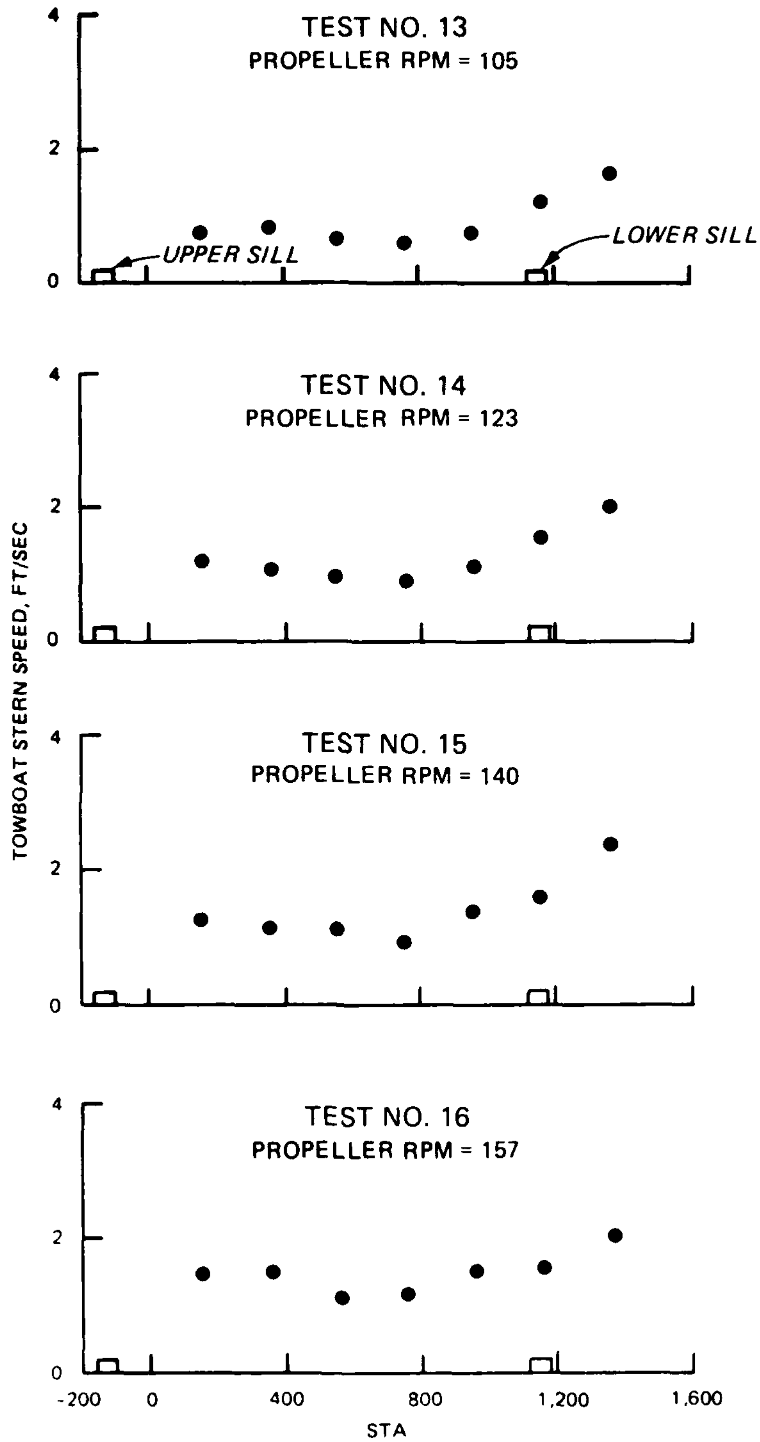
SPEED ALONG LOCK CHAMBER
TESTS 1-4



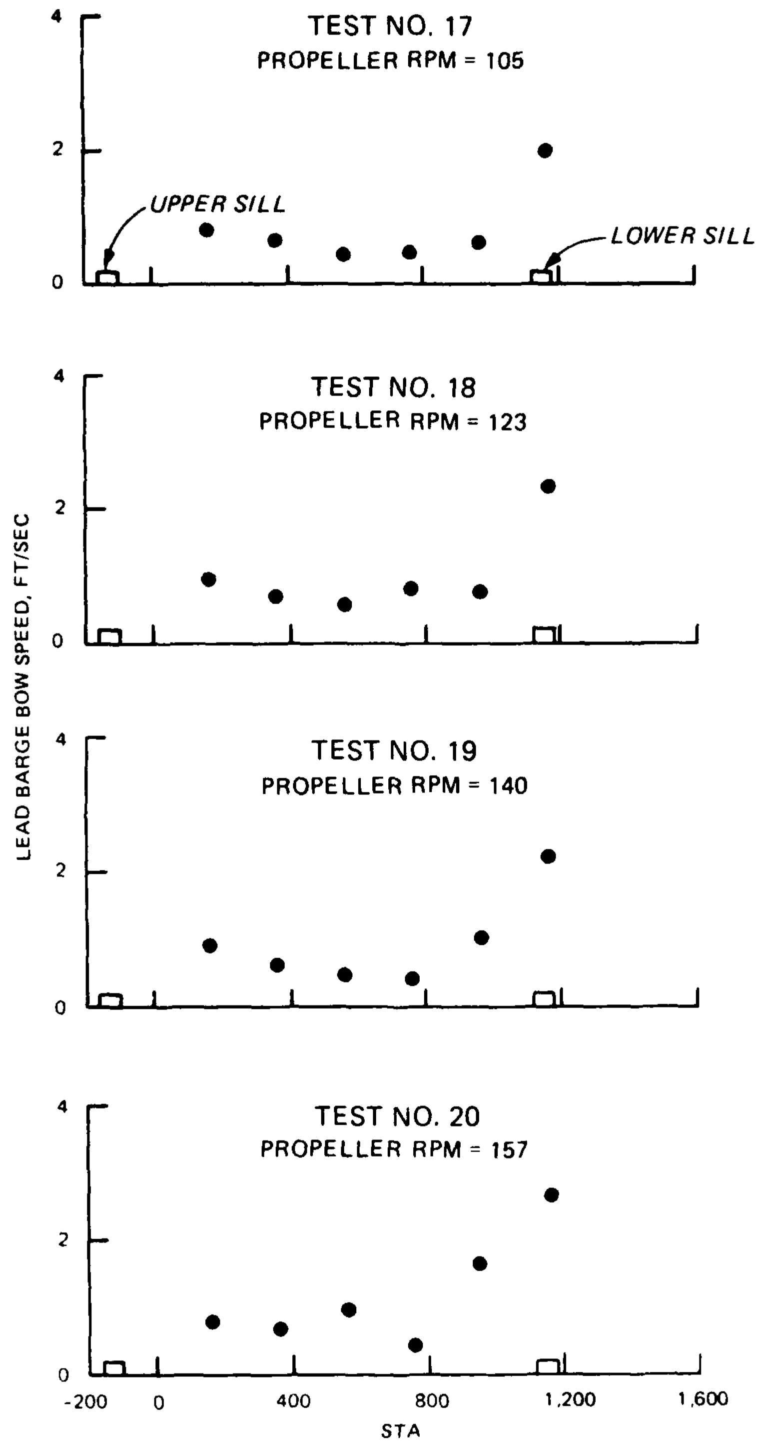
SPEED ALONG LOCK CHAMBER
TESTS 5 - 8



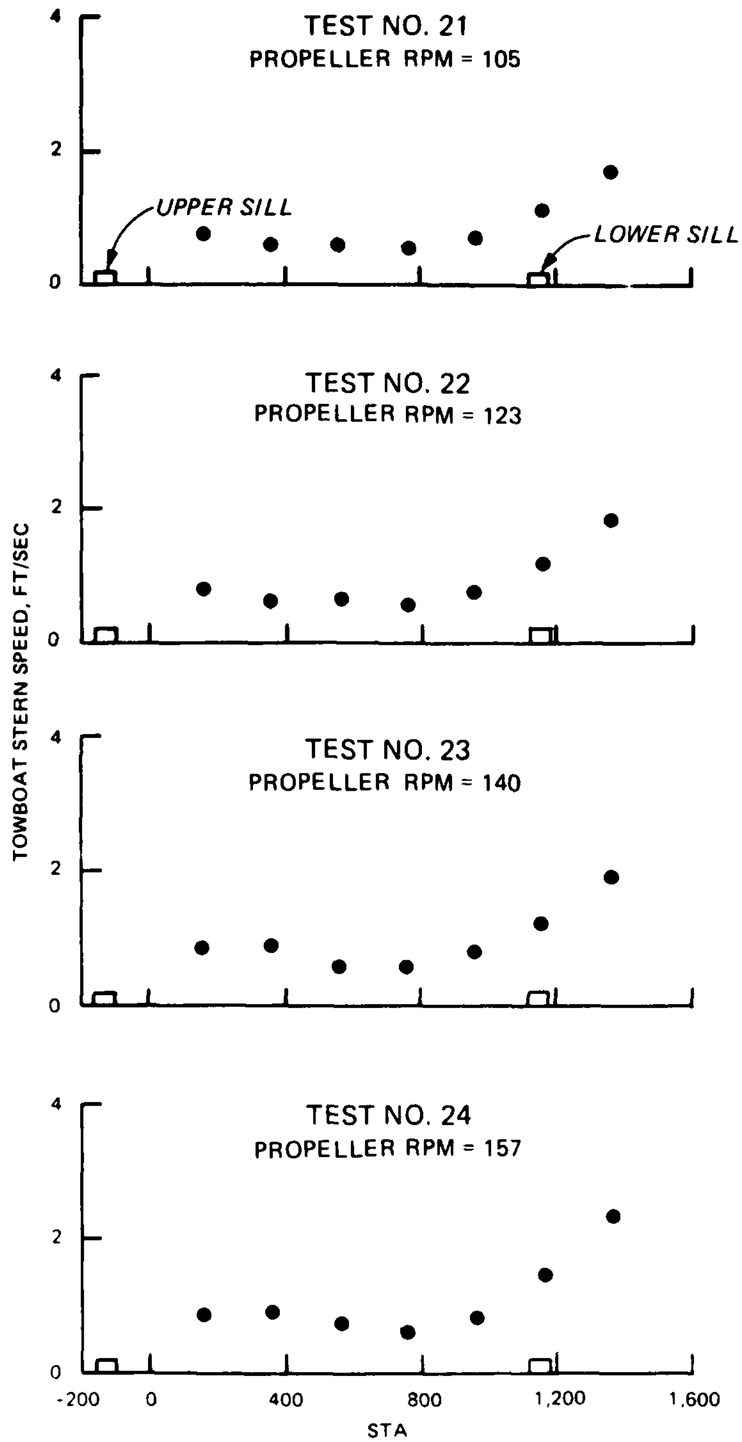
SPEED ALONG LOCK CHAMBER
TESTS 9 - 12



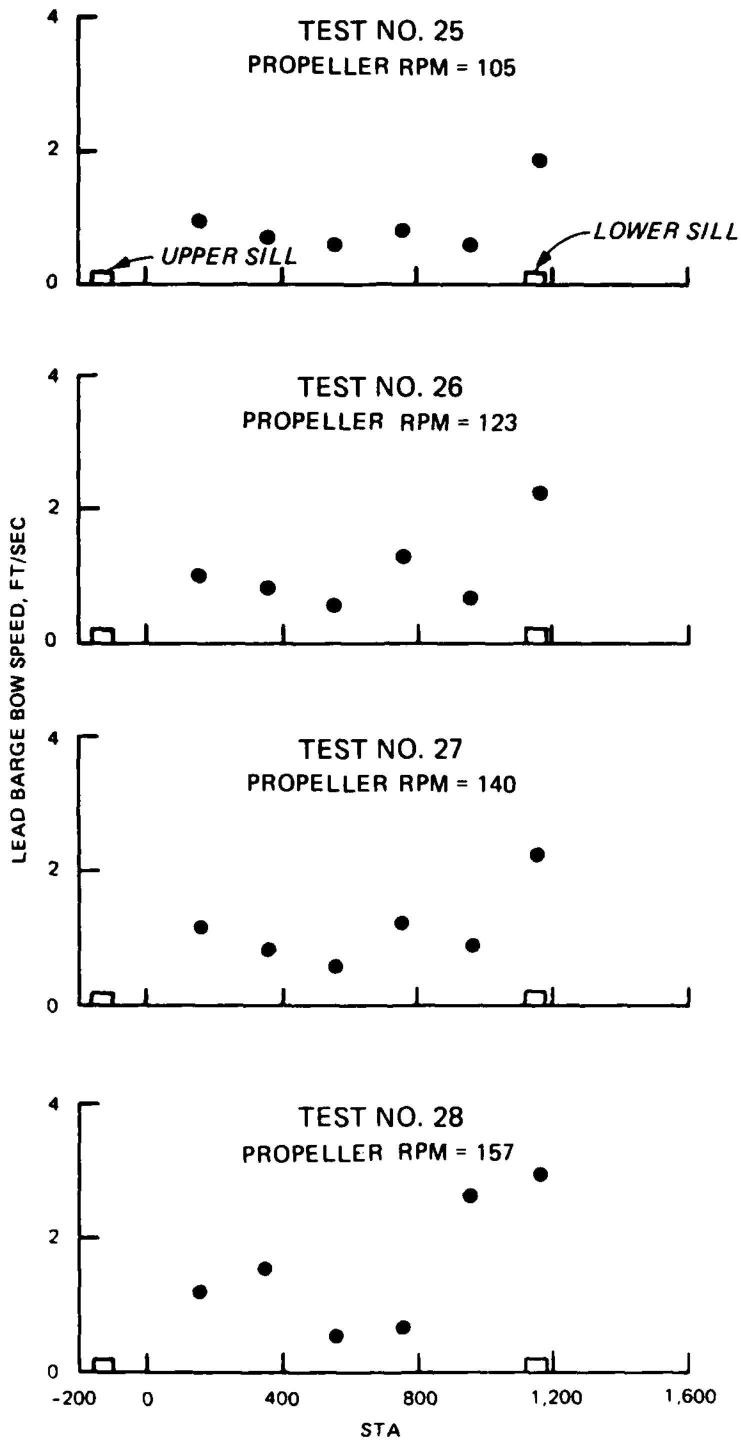
SPEED ALONG LOCK CHAMBER
TESTS 13 - 16



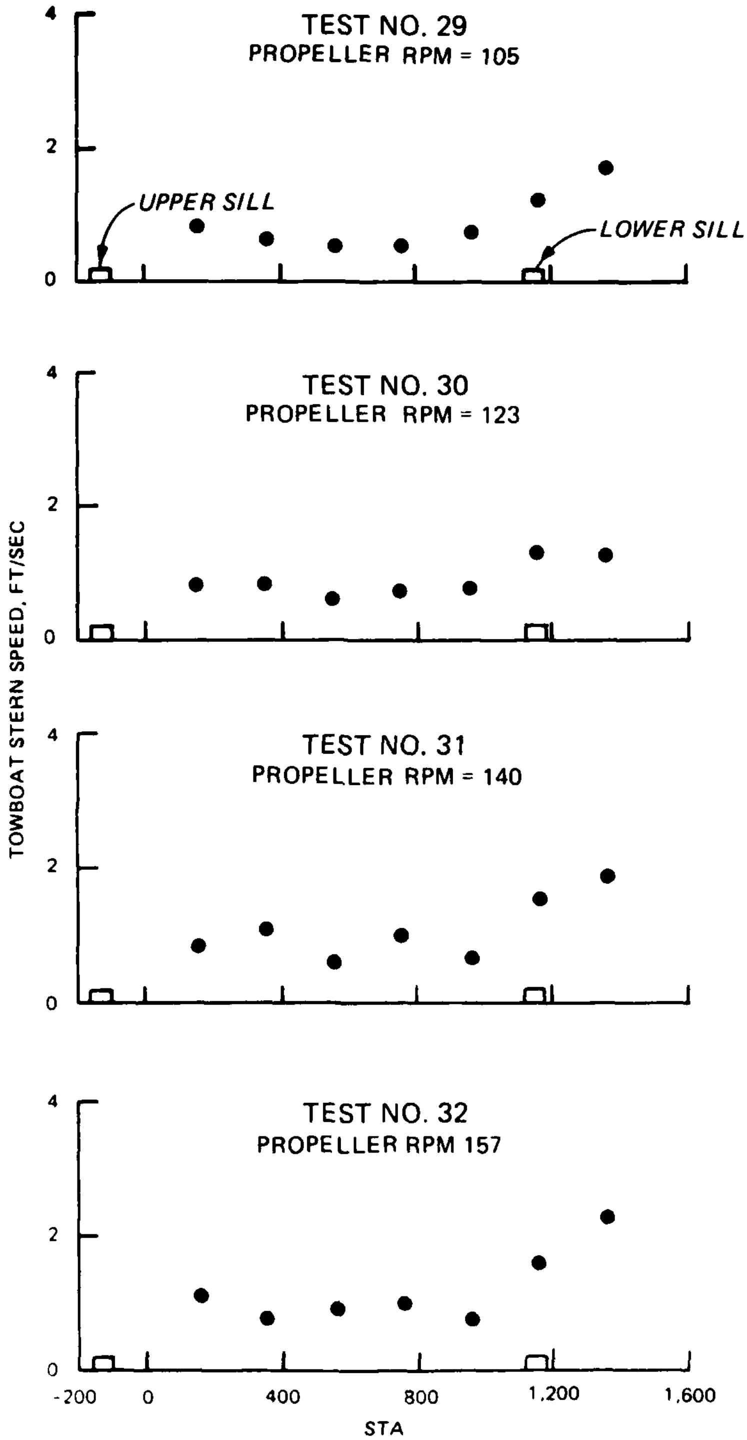
SPEED ALONG LOCK CHAMBER
TESTS 17 - 20



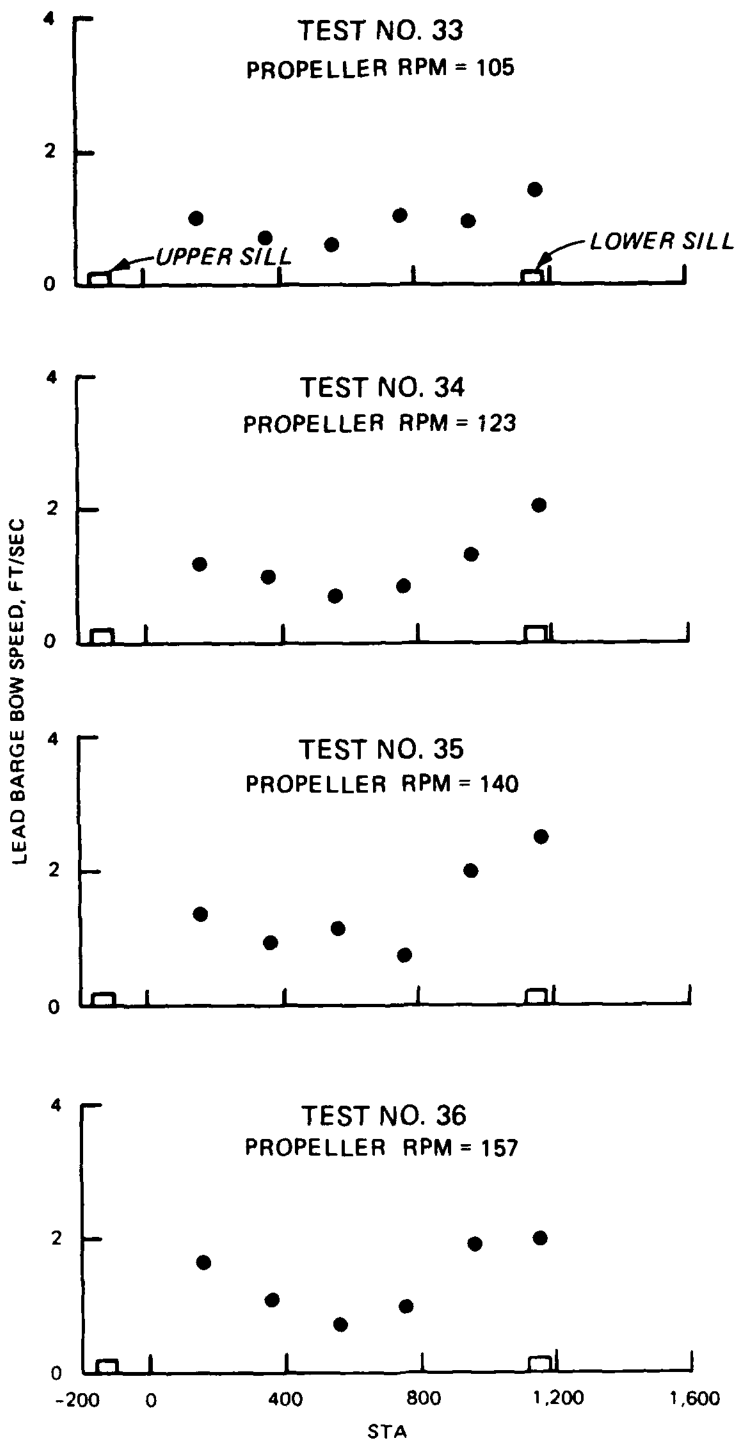
SPEED ALONG LOCK CHAMBER
TESTS 21 - 24



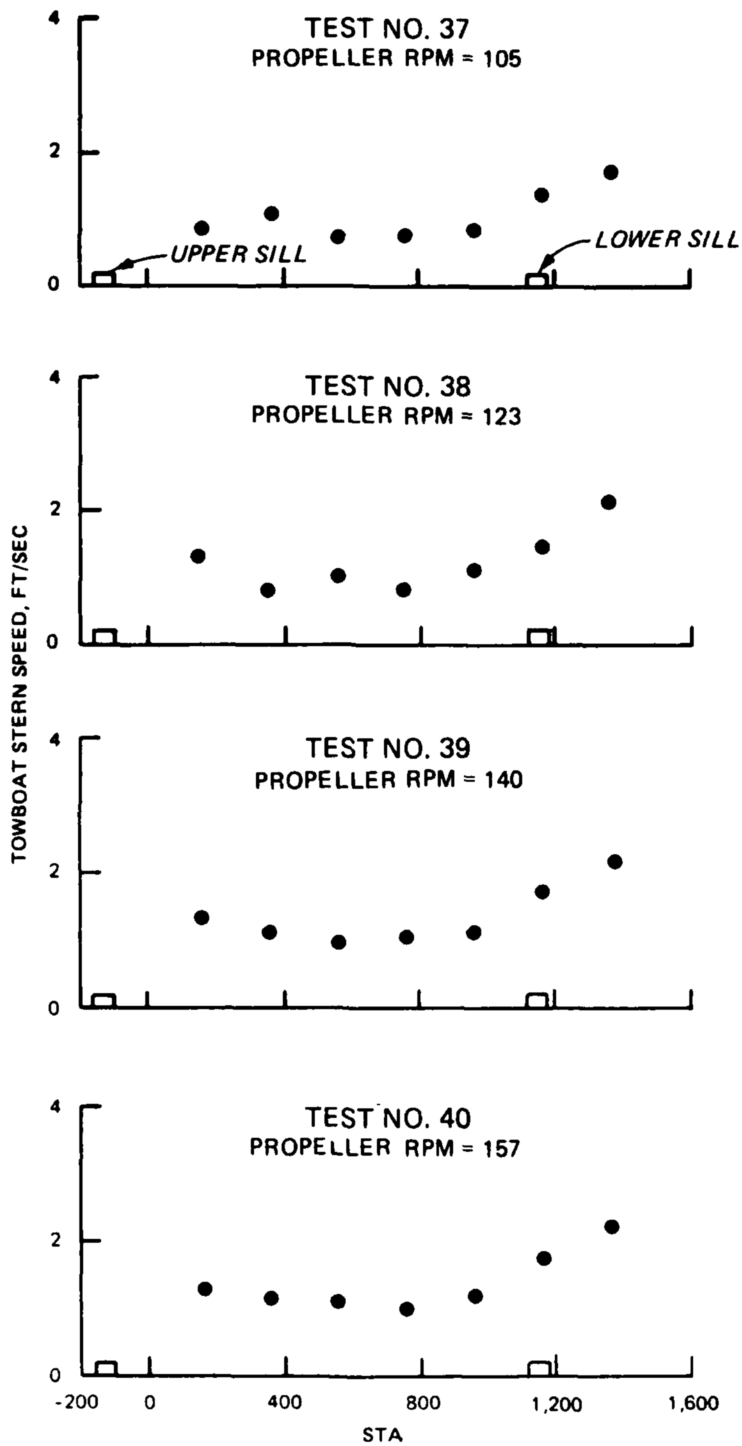
SPEED ALONG LOCK CHAMBER
TESTS 25 - 28



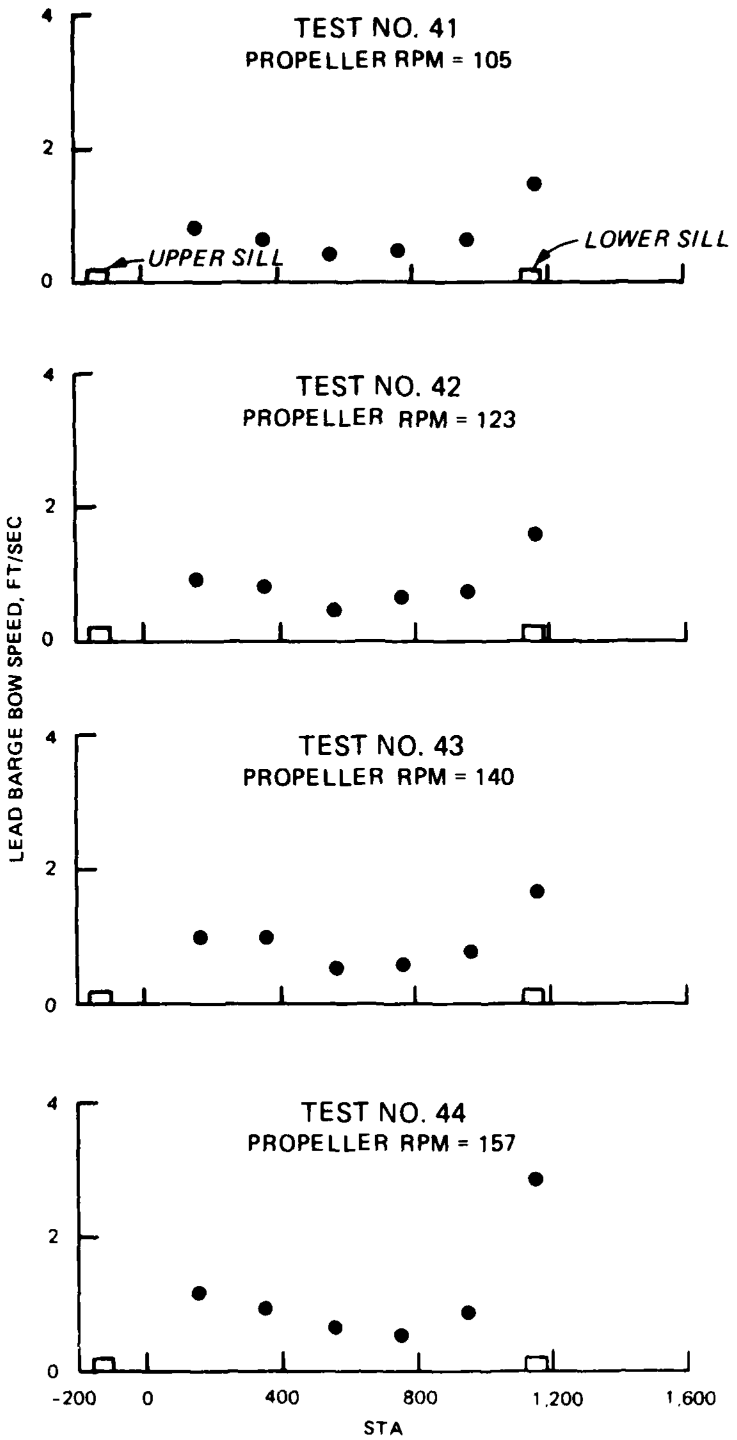
SPEED ALONG LOCK CHAMBER
TESTS 29 - 32



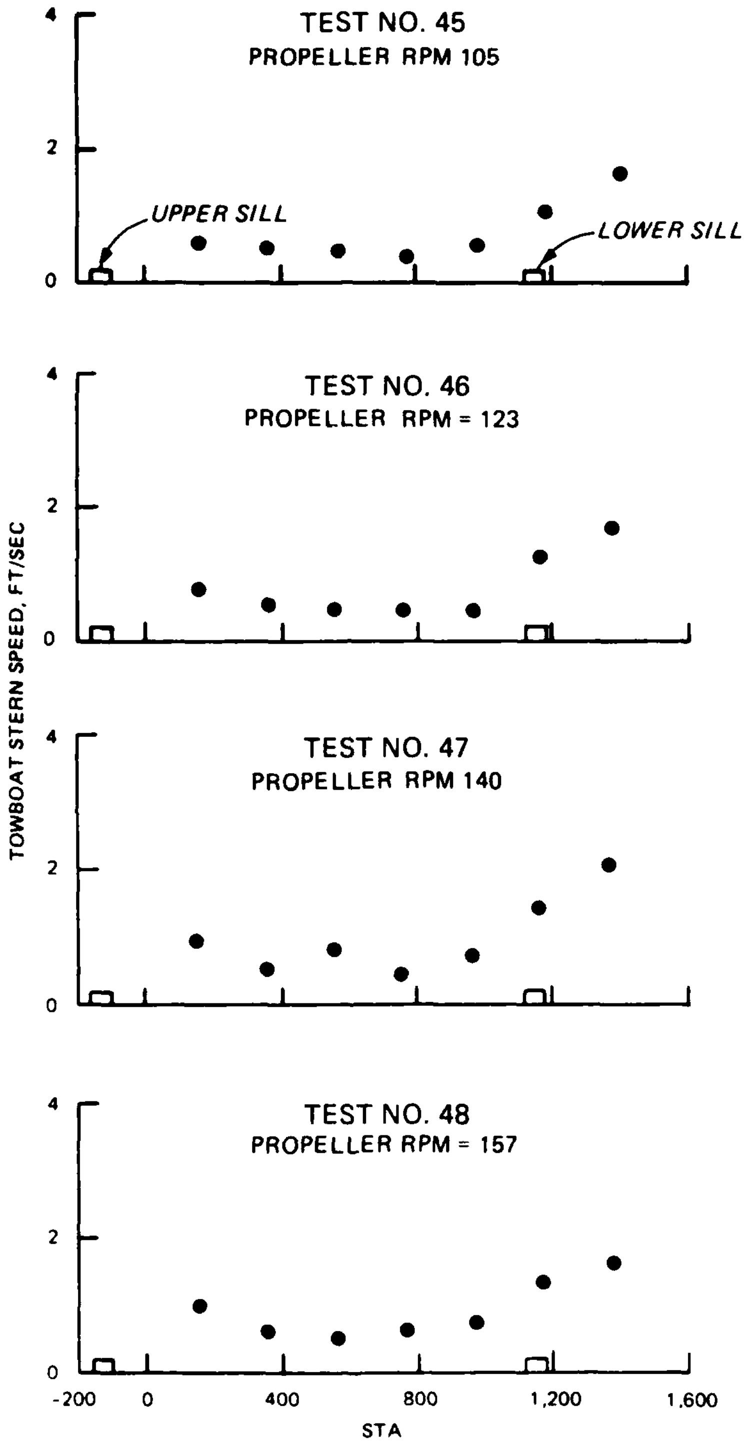
SPEED ALONG LOCK CHAMBER
TESTS 33 - 36



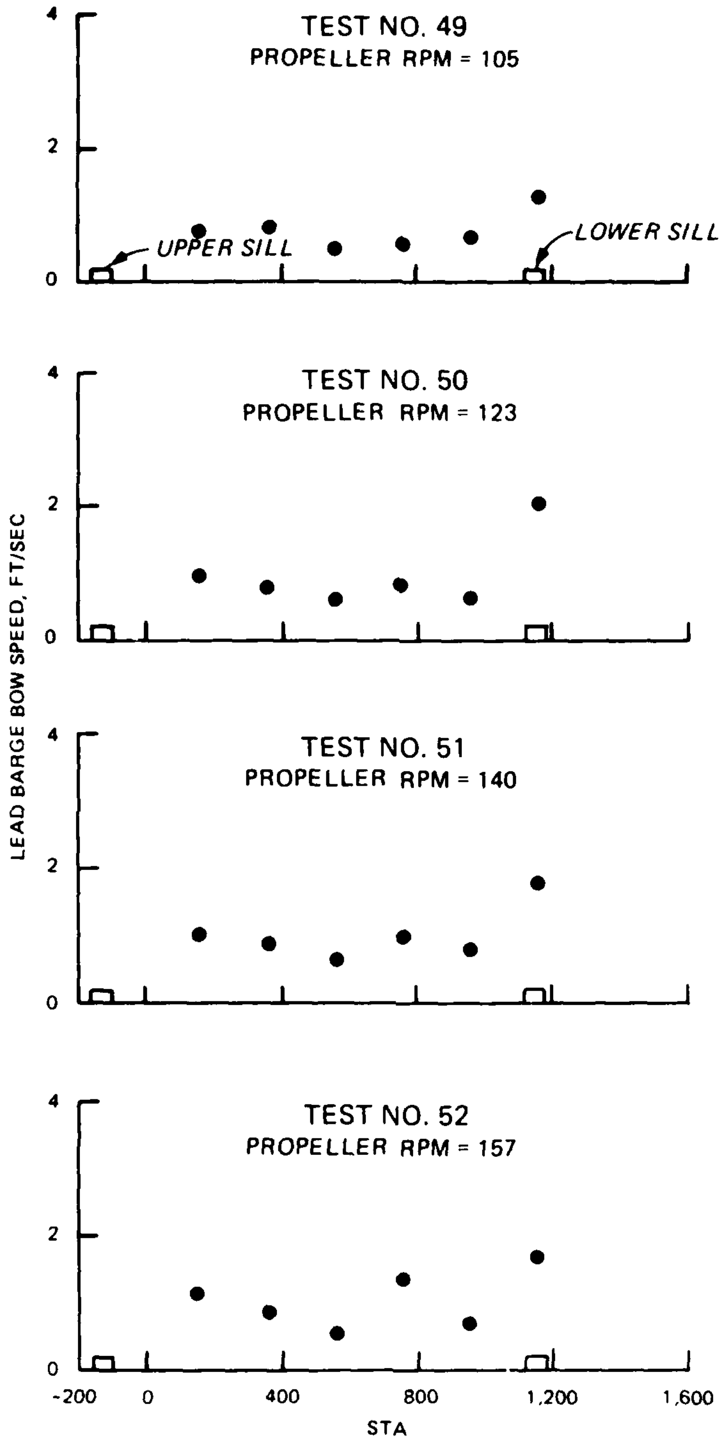
SPEED ALONG LOCK CHAMBER
TESTS 37 - 40



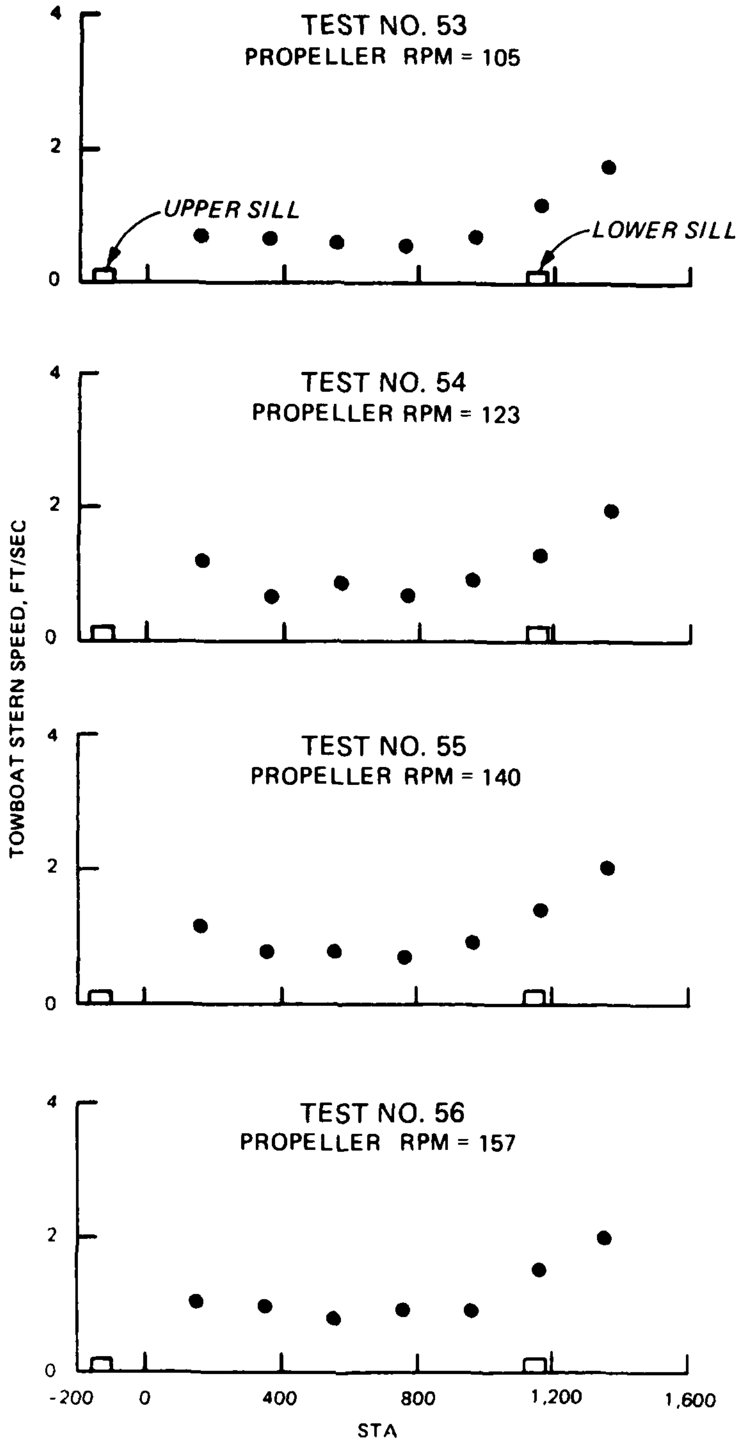
SPEED ALONG LOCK CHAMBER
TESTS 41 - 44



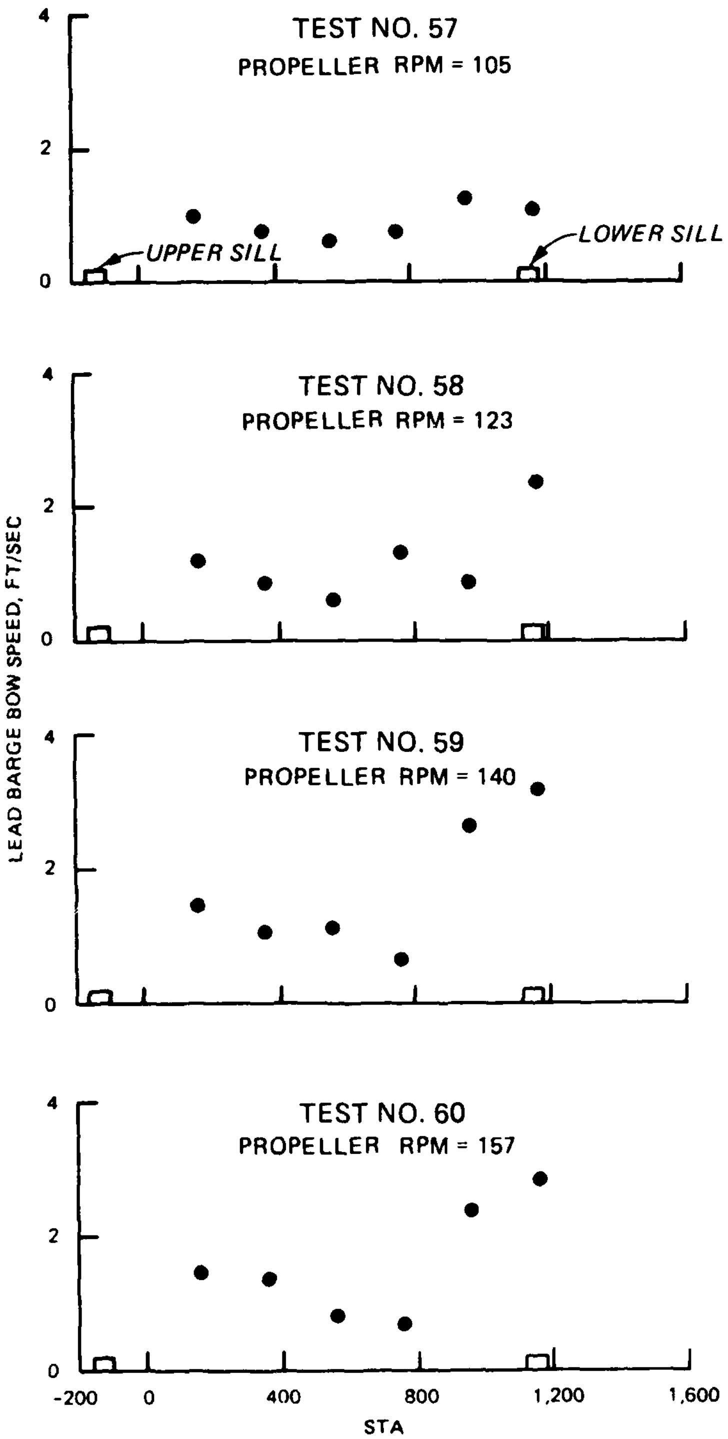
SPEED ALONG LOCK CHAMBER
TESTS 45 - 48



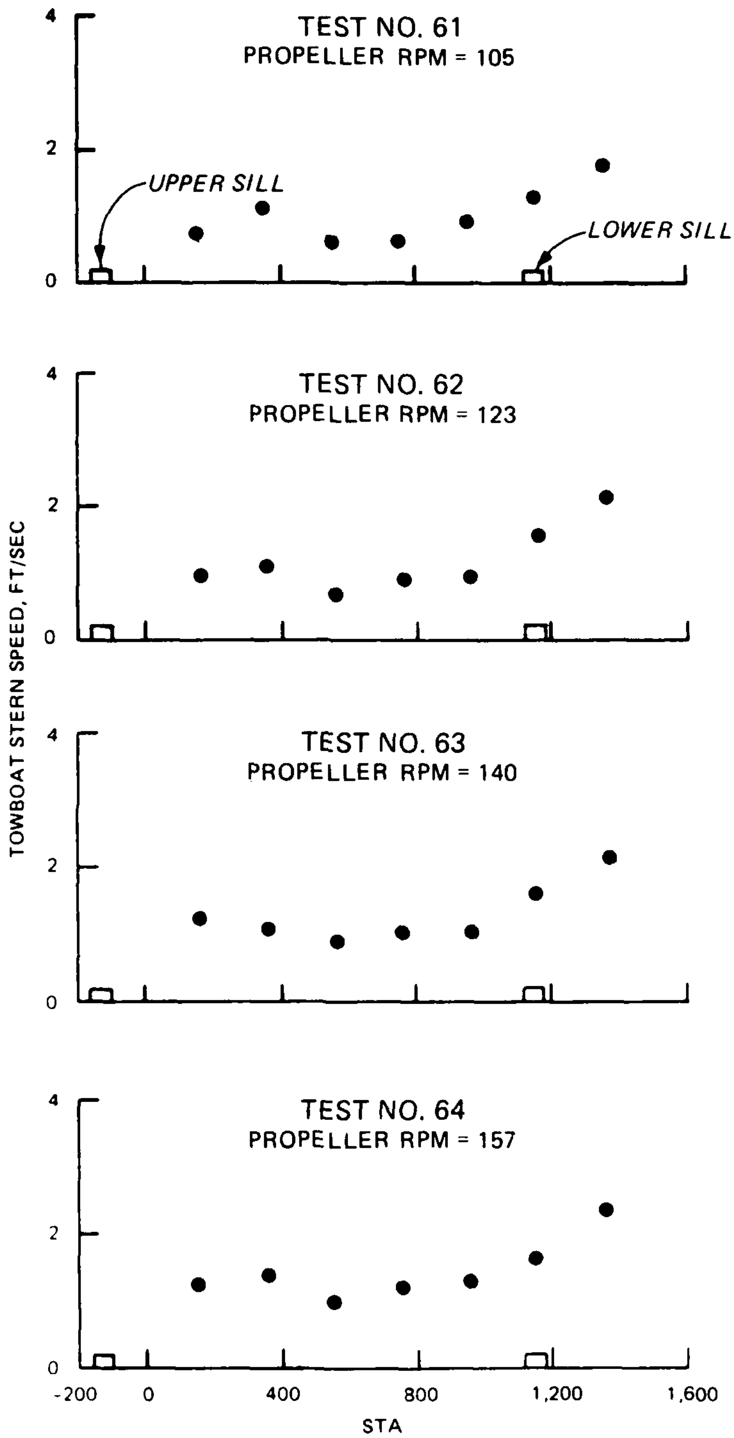
SPEED ALONG LOCK CHAMBER
TESTS 49 - 52



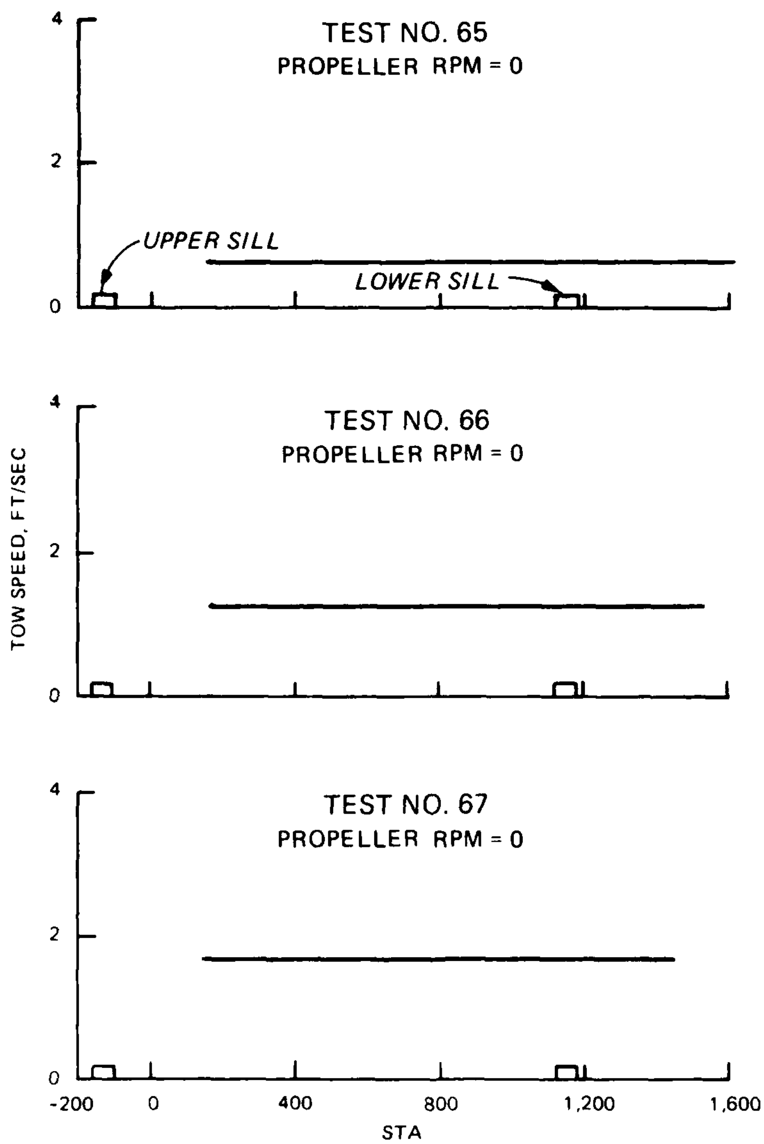
SPEED ALONG LOCK CHAMBER
TESTS 53 - 56



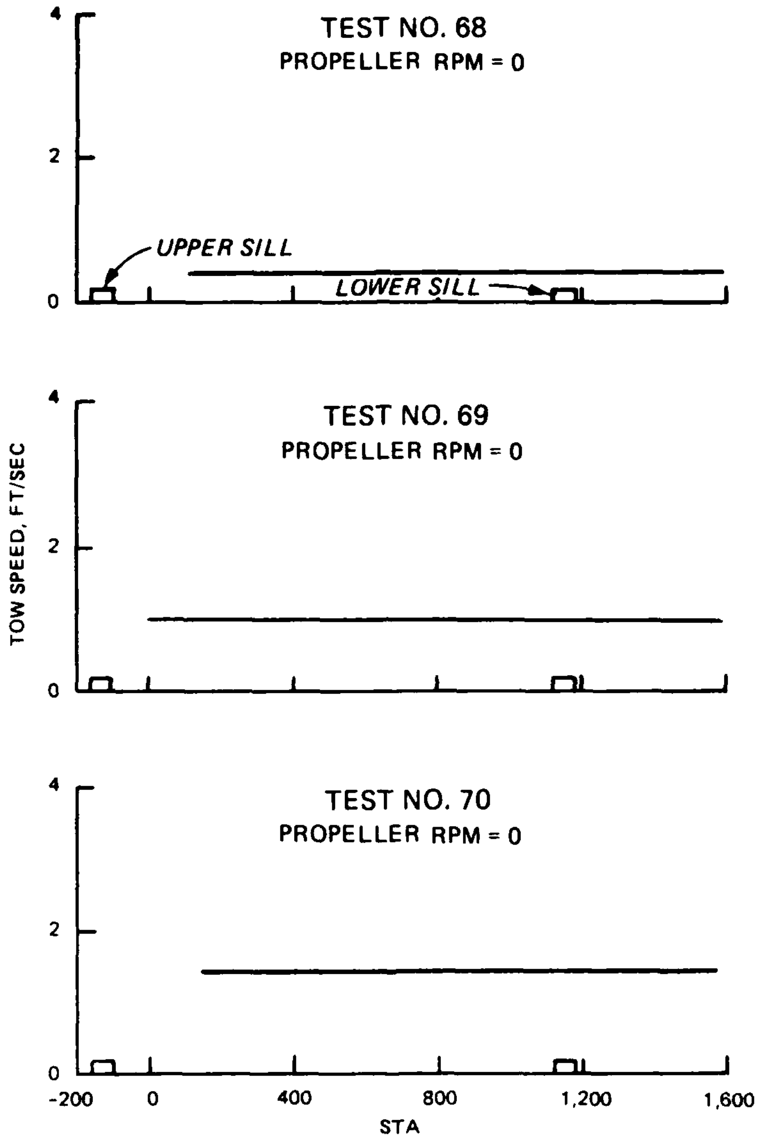
SPEED ALONG LOCK CHAMBER
TESTS 57 - 60



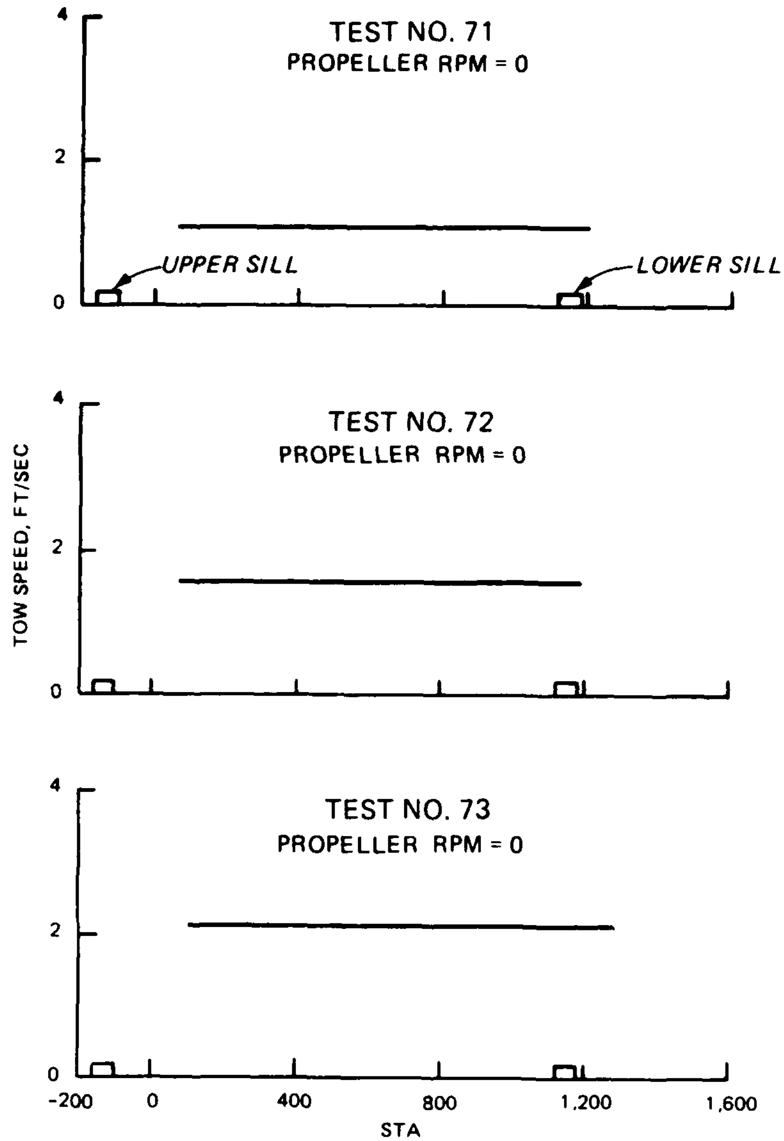
SPEED ALONG LOCK CHAMBER
TESTS 61 - 64



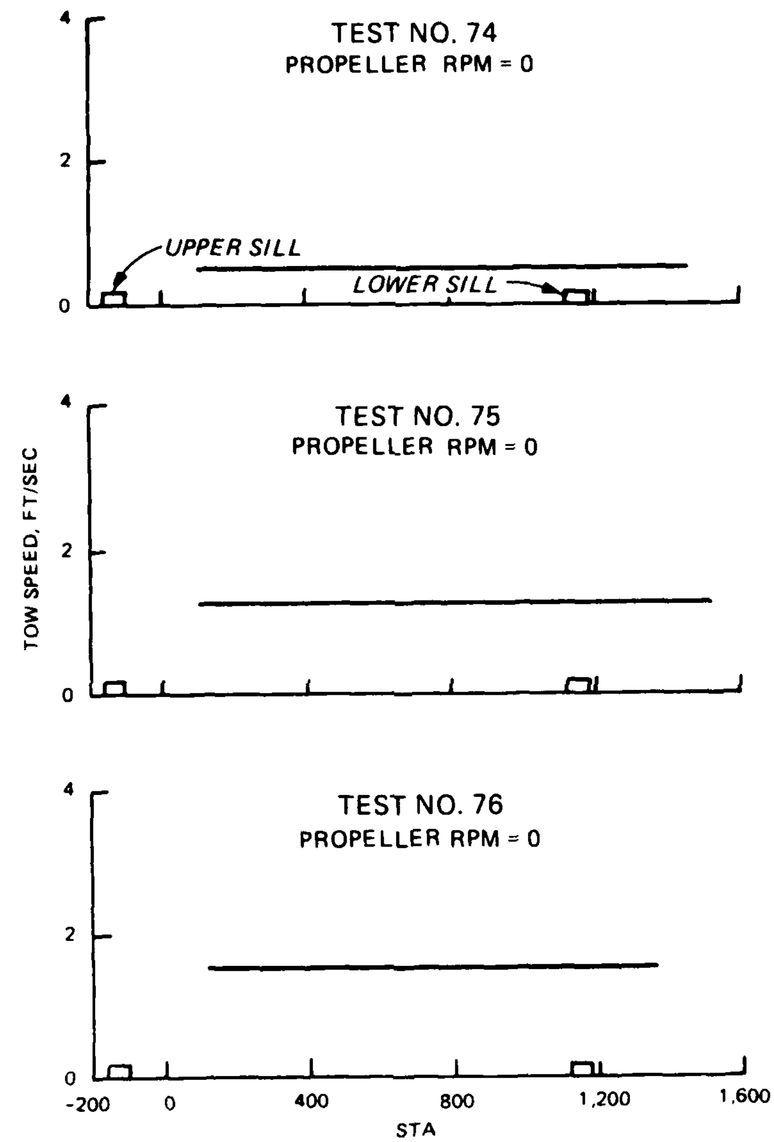
SPEED ALONG LOCK CHAMBER
TESTS 65 - 67



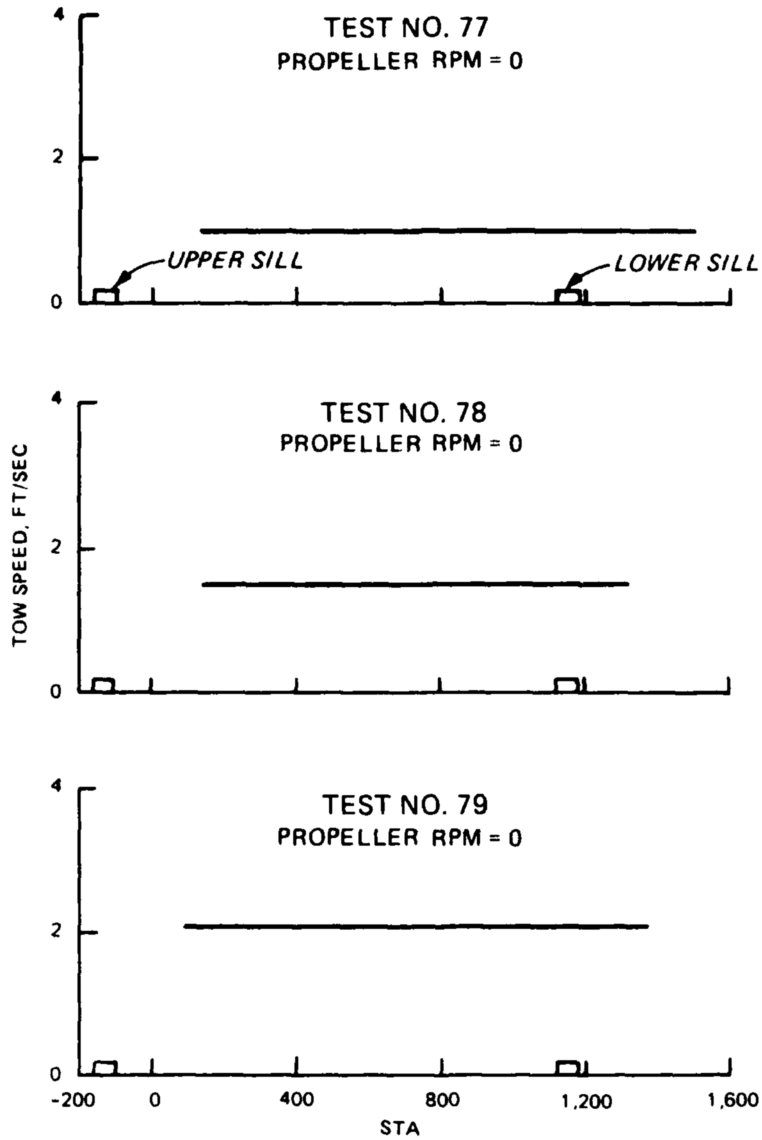
SPEED ALONG LOCK CHAMBER
TESTS 68 - 70



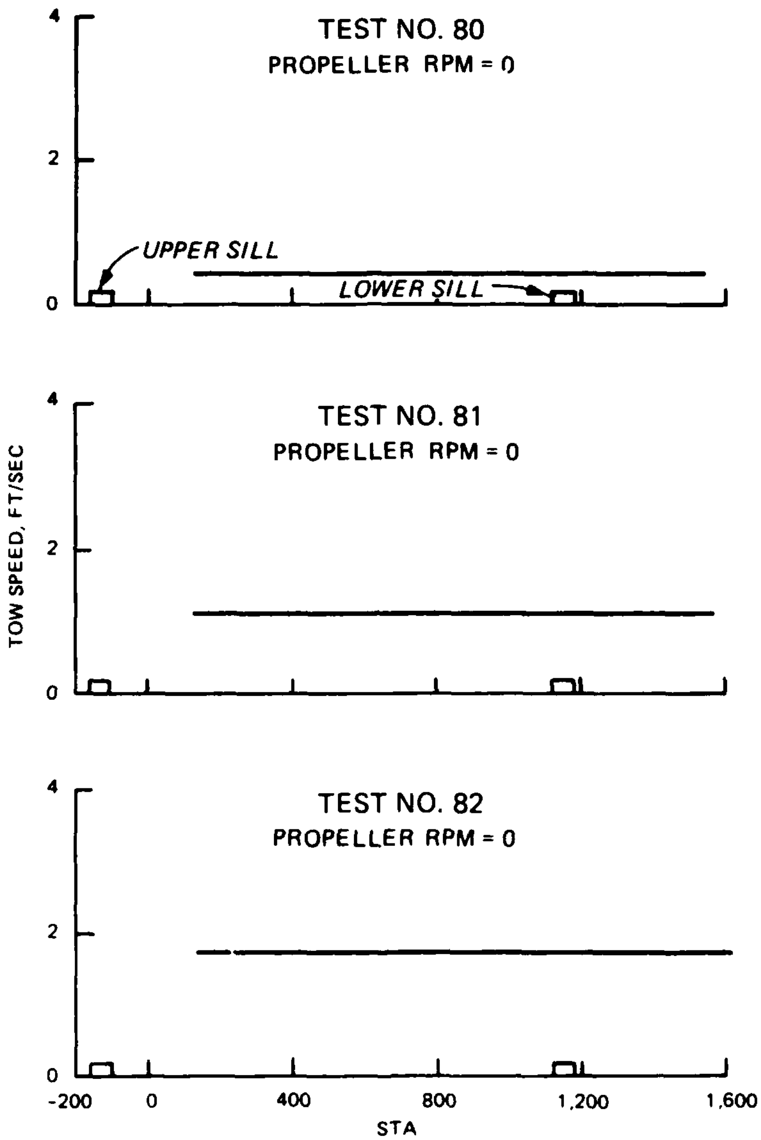
SPEED ALONG LOCK CHAMBER
TESTS 71 - 73



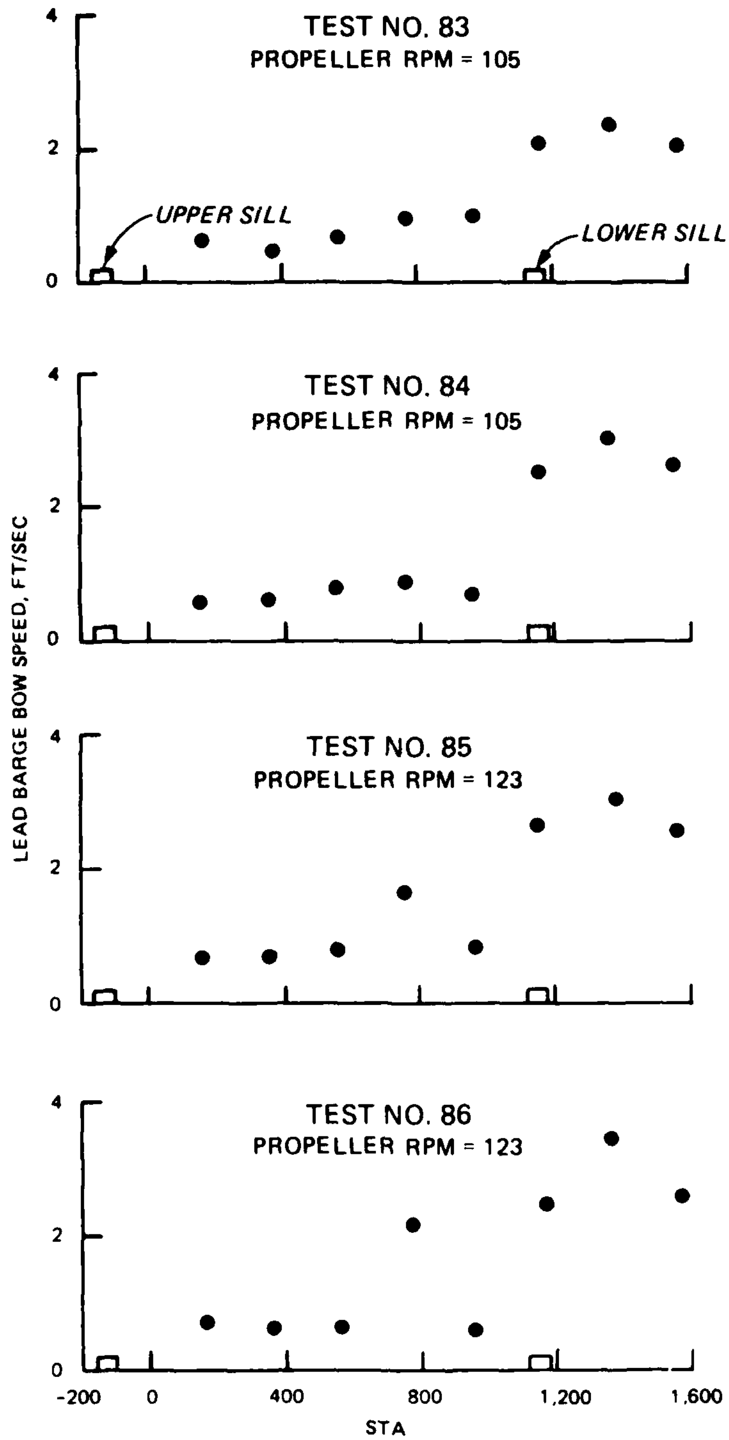
SPEED ALONG LOCK CHAMBER
TESTS 74 - 76



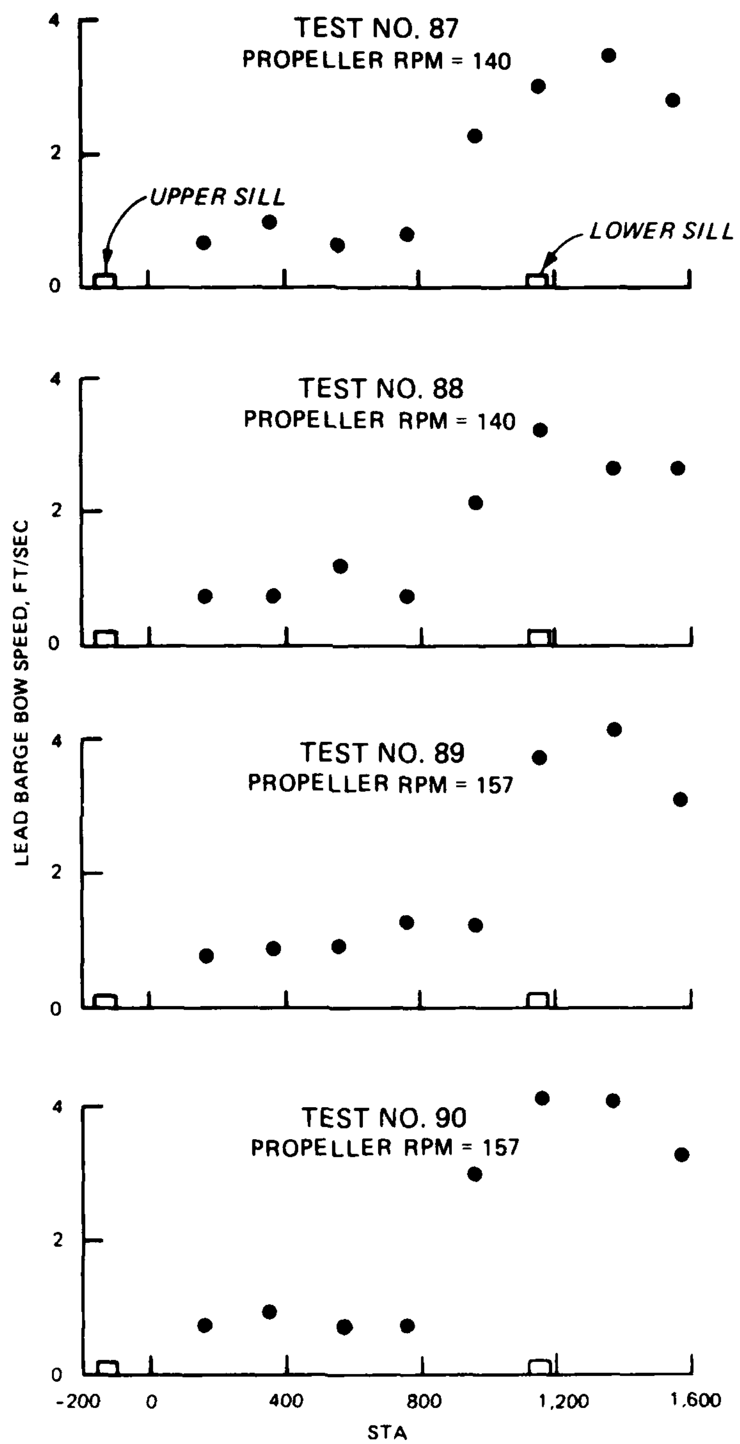
SPEED ALONG LOCK CHAMBER
TESTS 77 - 79



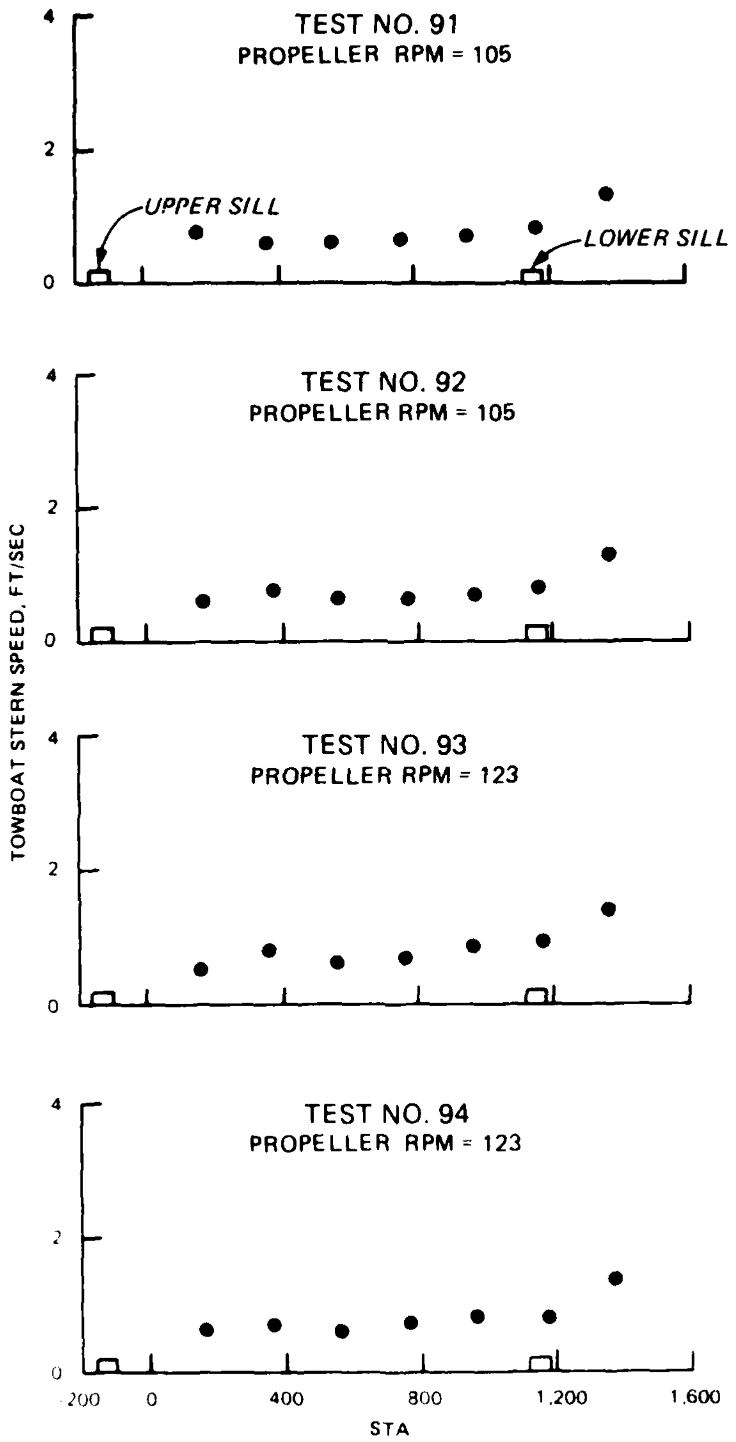
SPEED ALONG LOCK CHAMBER
TESTS 80 - 82



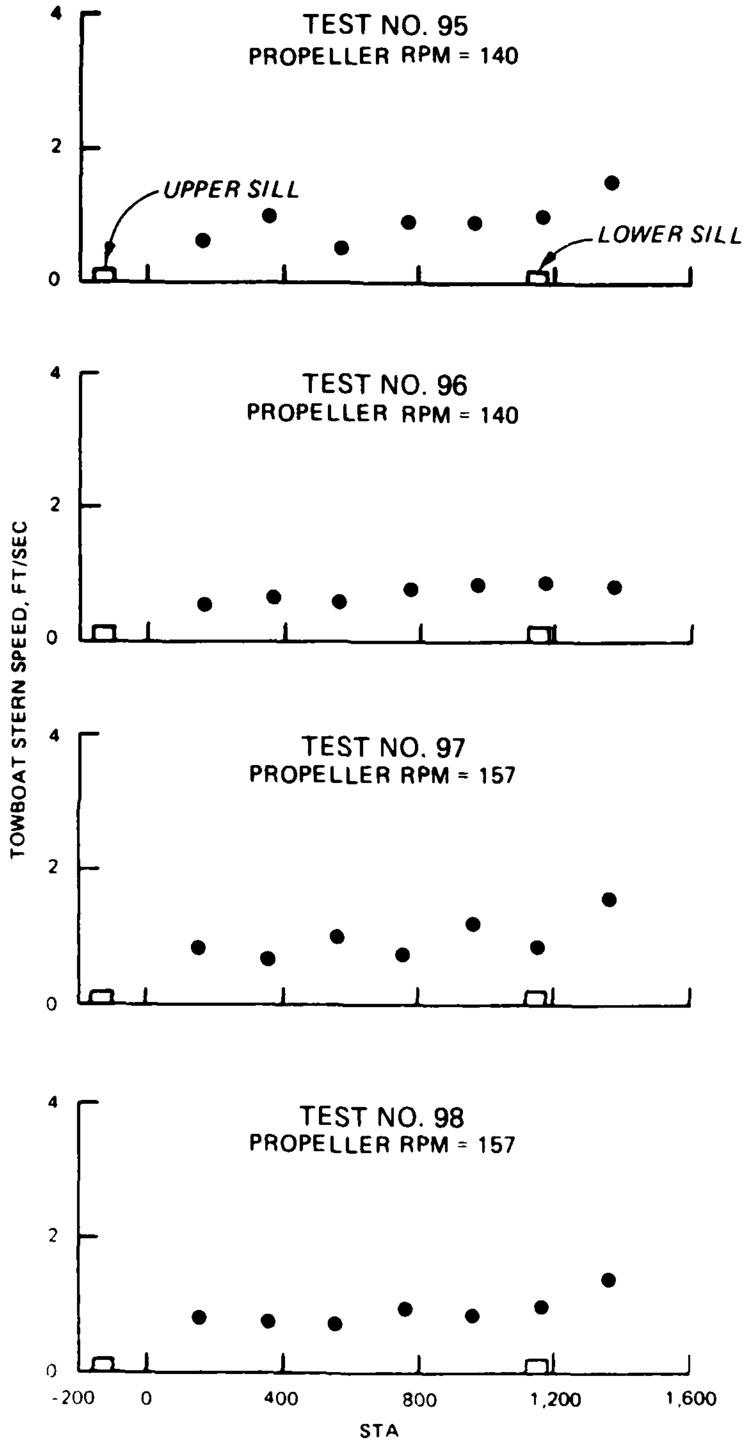
SPEED ALONG LOCK CHAMBER
TESTS 83 - 86



SPEED ALONG LOCK CHAMBER
TESTS 87 - 90



SPEED ALONG LOCK CHAMBER
TESTS 91 - 94



SPEED ALONG LOCK CHAMBER
TESTS 95 - 98

END

7-87

DTIC